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SCOPING MEETINGS FOR THE FEDERAL ENVIRONMENTAL ASSESSMENT PANEL REVIEW OF THE NUCLEAR FUEL WASTE MANAGEMENT AND DISPOSAL CONCEPT

SUBMISSION BY ENVIRONMENT CANADA

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Environment Canada Environnement Canada

This report has been prepared by Environment Canada's review team for the nuclear fuel waste management and disposal concept. Copies of the report may be obtained by contacting:

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SUMMARY

As part of the process for the Environmental Assessment Panel review for the nuclear fuel waste management and disposal concept, scoping meetings are being conducted to establish the basis of the Environmental Impact Statement (EIS) that must be developed by the proponent. The EIS will be the focal point of the Panel review and the hearings.

Environment Canada's overall responsibility is to represent the interests of the environment. As such, Environment Canada intends to be a party to the nuclear fuel waste management and disposal review to ensure that all matters regarding environmental protection are properly considered throughout that process. It should be noted that Environment Canada will not intrude into areas which are not within its mandate (e.g. human health effects), nor will it represent the interests of other groups or agencies during this review. Environment Canada will, however, exchange information (within its mandate) with other agencies or groups.

On October 22, 1990 Environment Canada made an oral presentation at the scoping meetings of the Environmental Assessment Panel. That presentation was a summary of some of the key issues of concern to Environment Canada. This document is a more detailed examination of the issues that Environment Canada feels should be included within the scope of the Panel review, and thus in the Environmental Impact Statement guidelines.

Environment Canada wishes to ensure that the best possible environmental protection practices and technologies are used for the handling, storage, and disposal of all wastes associated with nuclear electric power generation in Canada.

The questions of most concern to Environment Canada are:

What are the options for disposal that have been considered by the proponent?, and

Will the options that have been chosen safeguard the environment?

To address these two questions, Environment Canada's goal is to have the proponent rationalise the choices that have been made in the development of the disposal concept relative to all possible options, in particular those that have been studied and selected by other countries. The proponent should justify that they have

selected the best casks in which to transport the fuel, the best container in which to package the spent fuel, the best geological medium in which to build the repository, the best buffer and backfill material with which to surround the containers and refill the repository, the best grout with which to seal fractures and joints adjacent to the repository, etc. Further, the review must show that the environment will be protected not just during the construction and operation of the facility, but over the long-term life of the wastes.

This submission, after providing a background with respect to Environment Canada's interests and responsibilities in this review, presents a series of issues of concern to the department. These issues have been grouped into those of general policy and technical interest, as well as those that relate specifically to waste production and storage, transportation, surface facilities, subsurface facilities, geosphere, biosphere, social issues and public participation, economics and financing, and modelling and quality assurance and quality control considerations.

Highlighting our major concerns under each of the headings in this submission, topics that should be fully addressed in the EIS include:

General Policy

Given the scope of the concept and its associated complexities, the time allowed the intervenors to review the completed EIS should be at least eight months, perhaps more depending upon the length and complexity of the EIS. Supporting scientific and technical documents used to prepare the EIS must be published by AECL at least six months before submission of the EIS.

A key decision that has to be made is whether permanent disposal is a better choice than secure long-term retrievable storage. This decision must be made taking into account social, economic and environmental factors. With respect to the environment, the EIS must demonstrate that permanent disposal poses no unacceptable threats to environmental safety since, any release of environmental significance from a sealed repository would be inaccessible and could therefore not be readily corrected. We must be convinced that permanent disposal is the most appropriate option that could be selected at this time.

General Technical

Atomic Energy of Canada Limited (AECL) should be required to justify the various elements of its concept in terms of basic principles and international knowledge, to show that the concept is based on the best available technology and the most advanced scientific understanding.

The effects of events of low probability, but of potentially great environmental significance, (seismic disturbances, climate change, unintentional intrusion into the repository, etc.) must be evaluated as to how they may affect the concept.

Past waste management practices of the proponent, and of Canadian utilities operating nuclear generating stations, are important indicators of what could be expected in terms of safe handling of spent fuel wastes. These should be presented in the EIS.

Waste Production and Storage

All waste materials of any kind, normally or potentially capable of emitting ionizing radiation (spent fuel, reactor components, possible future reprocessing wastes, etc.), which will or may result from nuclear power generation, should be included in the review.

The containers used to house the spent fuel bundles should be assessed against severe conditions and compared with designs proposed by other countries.

Given that the proposed repository will be in operation far beyond the design life of reactors now operating, and into a period during which nuclear technologies will undoubtedly undergo major changes, it is important that the environmental impact statement address the concept's flexibility to safely handle and dispose of all forms of high-level nuclear wastes associated with nuclear power generation.

Transportation

Attention should be paid to the transportation cask, and proposed methods of transport and handling, to address issues such as dual purpose storage/transportation casks and anti-sabotage designs.

A reference transportation system should be developed to consider all elements of transportation needs, including waste form; cask type; mode, frequency, size and number of shipments; routes; support facilities; emergency planning. Potential risk, adverse impact, and response and contingency measures should be included in the reference transportation system.

Surface Facilities

In addition to an assessment of the primary facility and its ability to safely handle and process high-level nuclear wastes, AECL should determine the environmental impacts of ancillary activities (water use, clay mining, rock stockpiling, preparation of grout mixtures, container fabrication, etc.) associated with the development and operation of surface facilities. This assessment should include a comparison between a single large disposal facility versus smaller regional sites.

The process(es), techniques and criteria that could be used to characterise and identify sites for a disposal facility; the determination of the priority, costs and benefits of dedication or use of a site for activities connected with radioactive waste disposal compared with other present or potential uses of the same site or sites; and the availability of potentially suitable sites should be documented.

Subsurface Facilities

The materials used in construction and closure of the repository (e.g. buffer, backfill, sealant) must be shown to withstand the anticipated subsurface conditions over a sufficiently long period so as to conclusively demonstrate the long-term integrity of containment.

The effects of subsurface conditions (e.g. salinity, gases, high temperature, microbial activity) on the waste, the waste containers, the materials used in constructing and sealing the repository, radionuclide transport characteristics, and rock structure must be evaluated as to how they might affect performance criteria.

Uncertainties associated with subsurface processes (e.g. geomechanical stresses), and the way they could influence the development of the vault and its subsequent integrity as a containment facility, and consequent release to the environment, must be fully documented and addressed.

Geosphere

The adequacy of plutonic rock as a host rock and as a barrier to radionuclide transport must be justified in comparison with other rock types in Ontario.

AECL must demonstrate its ability to identify and characterise subsurface transport routes and processes as part of the procedure to evaluate potential disposal sites.

The EIS must explain how groundwater flow systems (including their depth, lateral extent, recharge and discharge zones, travel times, and factors likely to result in changes in these characteristics) will be defined in plutonic and surrounding rocks so that reliable estimates of radionuclide migration from the vault to the biosphere may be made over the entire period for which the radioactive wastes are to be contained.

Biosphere

AECL must demonstrate an advanced understanding of the movement through the biosphere of radionuclides and other elements of potential concern such that a credible environmental risk assessment can be undertaken. This assessment must include an evaluation of releases from the repository, and the effects of those releases on reference environments at the individual organism, species, community, and broader ecosystem level.

The components of the "reference environments" must be properly defined, must include factors to reflect sensitive ecosystem components (e.g. endangered species), and their models should be calibrated with parameter values associated with the differing environments of the Canadian Shield.

Social Issues and Public Participation

The EIS must incorporate a discussion of the social impacts of the proposed concept, and the methods that could be used to measure and mitigate them.

Public participation processes in other jurisdictions should be reviewed to ensure that the procedures available to Canadians in this review, provide at least as good an opportunity for review and discussion of environmental issues as those elsewhere.

Economics and Financing

Cost estimates must be made for siting, construction, operation, closure, and monitoring of a high-level radioactive waste disposal facility. This information is required to determine the feasibility of building such a facility (and its optimum size), to assess the economic impacts, and also to provide net or overall cost figures that can be used to assess the role of nuclear power as one of many energy options.

The proponent should provide a risk-benefit analysis of key components of the disposal concept to illustrate the degree of balance in the concept, relating to costs versus reductions in risk to the environment.

Modelling and Quality Assurance/Quality Control

AECL must demonstrate that its models have been verified and validated and can be used with confidence to conduct environmental and safety assessments.

The proponent must present a comprehensive quality assurance/quality control program for the entire concept.

This submission contains many more individual recommendations, all of which Environment Canada considers worthy of being addressed in the Environmental Impact Statement guidelines being developed for AECL. The submission is also accompanied by a technical appendix which provides a more detailed discussion of many of the issues of special concern.

In conclusion, Environment Canada believes that the Environmental Impact Statement should prove beyond a doubt that the proposed concept is not only the safest, but also the best option available now, and for the future. The EIS should contain the proof that the environment can be safeguarded, not just during any near future construction or operation phases, but most importantly over the entire long-term design lifetime of the disposal facility.

INTRODUCTION

1.0 GENERAL

The Governments of Canada and Ontario, through Atomic Energy of Canada Limited (AECL) and Ontario Hydro, have, since the late 1970s, been exploring ways of permanently disposing of spent nuclear fuel from CANDU reactors. As a result of that work, a concept has been developed by AECL and Ontario Hydro to dispose of the waste deep in the rock of the Canadian Shield.

In October 1989 the federal Minister of the Environment appointed an Environmental Assessment Panel to review the disposal concept, to hold public hearings, and to make recommendations regarding the concept's acceptability. The Panel has been instructed to examine the AECL/Ontario Hydro concept together with nuclear fuel disposal technologies being developed in other countries. The Panel review will be limited to the concept of deep geological burial, and therefore will not consider any specific sites for such a facility. The decision on whether to advance to the siting stage will have to be made based on the findings of the Panel.

As part of the Panel review process, scoping meetings are being conducted to establish the basis of the Environmental Impact Statement (EIS) that must be developed by the proponents. The EIS will be the focal point of the Panel review and the hearings. Interested parties have been invited by the Environmental Assessment Panel to identify issues that they believe should be incorporated into the guidelines that the Panel will issue to AECL for the preparation of its EIS.

Environment Canada's responsibility is to represent the interests of the environment. Thus, Environment Canada intends to be a party to the review process to ensure that all matters regarding environmental protection are properly considered throughout that process.

On October 22, 1990 Environment Canada made an oral presentation at the scoping meetings of the Environmental Assessment Panel. That presentation was a summary of some of the key issues of concern to Environment Canada. This document is a more detailed examination of the issues that Environment Canada feels should be included within the scope of the Panel review, and thus in the Environmental Impact Statement guidelines. The

submission begins by presenting the reasons for Environment Canada's interest in the review process, through discussions of its mandate, role and responsibility. It then moves on to give recommendations on specific issues. The issues have been grouped in categories corresponding to the major elements of the disposal concept. They begin with some general policy and technical issues and then proceed to waste production and storage, transportation, surface facilities, subsurface facilities, geosphere, and biosphere. The submission concludes with a discussion of three groups of issues that must be reflected in any review of this magnitude, those involving social concerns and public participation, economics and financing, and quality assurance and quality control of the computer models used to conduct environmental assessments.

Each of the major technical issues identified by Environment Canada is supported by material in a Technical Appendix which accompanies this report. These technical issues are of special concern to Environment Canada, and are ones that require the greatest attention by AECL in the preparation of its EIS.

2.0 MANDATE OF ENVIRONMENT CANADA

The mandate of the Department is to foster harmony between society and the environment for the economic, social and cultural benefit of present and future generations of Canadians.

The Department of the Environment Act provides Environment Canada with the general responsibility for environmental management and protection. DOE is responsible for providing environmental advice to federal government departments, and for the preservation and enhancement of environmental quality.

In 1988 the House of Commons Standing Committee on Environment and Forestry produced a report, "High-Level Radioactive Waste in Canada: The Eleventh Hour". One of the recommendations in the report was that as part of its mandate, "Environment Canada should rapidly assemble resources with a view to defending the environmental standpoint during the upcoming debate on the Canadian nuclear fuel waste management program". In its response to that recommendation the government agreed, saying that Environment Canada would review AECL's final concept assessment document and other documents and would prepare its own brief.

3.0 ROLE OF ENVIRONMENT CANADA

Section 36 of the Federal Environmental Assessment and Review Process Guidelines Order (June 1984) establishes the role of non-initiator and non-proponent departments during public environmental assessment panel reviews. That section states:

> "In a public review, it is the role of every department that has specialist knowledge or responsibilities relevant to a proposal to
>
> (a) provide to the Panel and any other participants in the public review any available data, information or advice that is requested from them;
>
> (b) provide experts at public hearings of the Panel to make presentations or to respond to questions; and
>
> (c) where appropriate, advocate the protection of the interests for which they have the responsibility."

4.0 RESPONSIBILITY OF ENVIRONMENT CANADA

Environment Canada will intervene before the Environmental Assessment Panel to assist them in ensuring that the impact that the proposed disposal concept will, or may, have on the environment is fully investigated and clearly documented by the proponent. Specifically, the department will:

> (a) submit to the Panel at its scoping meetings, those issues that it believes should be investigated by Atomic Energy of Canada Limited (AECL) and included in the Environmental Impact Statement (EIS) guidelines;
>
> (b) review the draft EIS guidelines prepared by the Panel based on the scoping meetings, and provide the Panel with advice regarding the comprehensiveness of the guidelines, as they relate to environmental issues;

(c) conduct a technical review of AECL's Environmental Impact Statement documents and other documents used to prepare the EIS, to address expected and predicted impacts, suitability of mitigative measures, suitability of assessment techniques, data gaps, accuracy and completeness of the information, and recommendations for future actions or studies; and

(d) prepare a departmental position that includes the magnitude of potential environmental impacts, and the degree to which the proposal complies with legislation and policies for which the federal Environment Minister is responsible.

Following completion of the Panel's report, Environment Canada will review the report and will, within its mandate prepare a response identifying the implications of the recommendations.

During its review of the disposal concept, Environment Canada will liaise with other government agencies and public interest groups to maintain an awareness of the concerns and actions of these groups. Environment Canada will not, however, infringe on the mandates or responsibilities of other government departments, nor will it represent the interests of other government agencies or interest groups (e.g. it will not comment on health effects which are the responsibility of Health and Welfare Canada).

ISSUES

The following numbered sections comprise a preamble, or rationale, for each issue deemed important by Environment Canada, and a recommendation (in bold lettering) to the Environmental Assessment Panel for inclusion of the issue in the guidelines to be submitted to AECL for the preparation of its environmental impact statement.

Many of these issues are discussed in greater detail in a Technical Appendix accompanying this submission. The Technical Appendix follows the same numbering system for ease of cross-referencing with the main document.

1.0 GENERAL POLICY ISSUES

1.1 Over a decade ago a decision was made that Canada would continue to use a once-through fuel cycle using natural uranium fuel. Research on a disposal concept for this fuel has been carried out and is ongoing. As research continues, technical progress in the reprocessing of spent fuel and other areas that may affect the decision to continue with a once-through fuel cycle can be expected.

AECL and Ontario Hydro[1] should address the factors that may affect a future decision to reprocess CANDU fuel. If it is possible that a decision to reprocess could be made prior to sealing of the proposed repository, the proponent must indicate the degree to which the proposed concept would be adaptable to this situation (i.e. to allow removal of waste for reprocessing as well as to accept reprocessed fuel and associated wastes).

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[1] It is recognised that Ontario Hydro and AECL are partners in developing the concept, and are therefore joint proponents. All recommendations concerning storage and transportation issues (i.e. those being the primary responsibility of Ontario Hydro) have been directed to both proponents. Those that relate to issues other than storage or transportation have been referred only to AECL.

The assessment of high-level wastes from the reprocessing of spent fuel should also outline the risks from the recovered fission products, and their means of ultimate disposal.

1.2 The concept of a deep geological repository for Canada's high-level nuclear waste makes the assumption that permanent disposal is needed.

AECL and Ontario Hydro should be required to address the alternatives to permanent disposal. They should also be required to review the economic, social, and environmental needs, costs and benefits associated with disposal versus other options, including secure yet retrievable long-term storage.

1.3 The terms of reference for the Nuclear Fuel Waste Management and Disposal Concept Environmental Assessment Panel state explicitly that, "In examining the future steps to be taken with respect to the management of nuclear fuel wastes in Canada, the Panel will take into consideration the degree to which we should relieve future generations of the burden of looking after the wastes."

One of the general premises in discussing the acceptable approaches to the disposal of radioactive wastes is that the wastes should not become a burden (physical or economic) to future generations. Those who benefit from an activity should also bear the cost of it - a principle which is generally known as the "polluter pays principle". It may be argued that many benefits are being passed on to future generations through the research and development of nuclear power, but these benefits may be difficult to quantify in the case of nuclear waste disposal.

Should we relieve future generations of the <u>economic</u> burden of looking after waste fuel, or of the burden of looking after it <u>physically</u>, or both? If the intent of permanent disposal is to free future generations from the economic burden of nuclear waste management, this could be done by establishing a fund large enough to cover all future costs. Thus, the permanent disposal concept is not required on the basis of economics, since an arrangement similar to a pension fund could be used by user generations to provide for all estimated future costs.

AECL and Ontario Hydro should be required to consider the manner and degree to which future generations should be relieved of the burden of nuclear waste disposal, and to identify and justify the basis on which the recommended disposal concept has been selected.

1.4 Should an unacceptable ecological situation occur necessitating investigative or corrective action, or the removal of high-level wastes from a repository, a contingency plan should be available to achieve this end. A preliminary plan of this nature should be incorporated into the disposal concept to facilitate response actions and any such retrieval/replacement process without compromising the long-term integrity of a repository.

AECL should develop contingency plans to respond to unacceptable conditions and to recover the wastes from the repository in the event that this ever becomes necessary. The plans should include measures to respond to various environmental release scenarios, the retrieval and handling, designs for surface storage over the short- and long-term, and replacement procedures, such that an acceptable level of integrity of all surface and subsurface facilities is always maintained.

1.5 The Environmental Impact Statement will be presented at public hearings. Our understanding is that this EIS will address all of the broad issues, but will recognise that many key technical issues are still being explored, and will therefore not be resolved before the hearings are complete. AECL has recognised this, and has planned ongoing research on key concept components until into the next century. The Panel should recognise that ongoing research will continue after the hearings, and that issues raised during the hearings may lead to a requirement for additional research. The concept, if approved, must be able to respond to new technical, social and environmental advances that will certainly come about during the development and operational life of the facility.

AECL should prepare a summary of all work, either planned or in progress, for which results will not be available until after the hearings. The summary should indicate for each piece of work, the reasons for the work, the expected results, the expected completion date, and any other relevant

information. AECL should also be required to identify in the EIS (or present their views on the need for) more research, and to respond to any further research needs that may be identified during the Panel review.

AECL should be required to present annual assessment briefings for new research and development, and associated supporting documentation.

2.0 GENERAL TECHNICAL ISSUES

2.1 The AECL concept for permanent disposal must be shown to be based on the best technology, practices, standards and scientific understanding to protect the environment from radioactive wastes. It should be clear from the EIS that the concept is internationally accepted and does not ask Canada to accept less strict measures of protection than other countries.

The decision to consider intrusive igneous rock (plutonic rock) as the disposal medium appears to have been made in 1975. Since that time little direct attention has been given to other geologic disposal media. Other countries have identified with characteristics which are potentially favourable for the geologic containment of nuclear wastes. Similarly , other reference environments may have different ecosystem attributes that may respond differently to potential releases from a waste repository.

The comparison of alternatives is a key issue in the concept review, and has already been recognised as such:

"Alternative methods for disposing of high-level radioactive waste must, in our opinion, be considered during the concept assessment review. It is not possible to decide upon the acceptability of a particular concept without comparing it to other concepts. Only when such a comparison is carried out can the advantages and disadvantages of the particular concept under review be discovered and given proper consideration, and the acceptability of the concept be decided upon."[2]

The proposed concept of plutonic rock disposal and other disposal concepts each have differing social, economic, and environmental consequences because each affects different ecological and human populations. Thus each may produce different levels of actual and perceived risk. In order to determine the degrees of impact generated by each concept, it will be necessary for each concept to be described at a similar level of detail as the present concept being proposed

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[2]AECL Report, "Public Consultation Program on Nuclear Fuel Waste Management: Identification of Issues, (page 14), July 1989, M.A. Greber, and R.B. Anderson.

by AECL.

AECL should review international practices for the management of spent nuclear fuel and other high-level radioactive waste, and should demonstrate in the EIS how their concept compares with those of other countries.

AECL should justify the choice of plutonic rocks in a boreal setting rather than alternative types of geological media in alternative reference environments. AECL should also indicate how their permanent disposal option compares - in terms of social impact, risk to the environment, and cost - with all other available options, including other geologic disposal media such as shale, clay or salt, either individually or in combination with crystalline rock. Each alternative concept should be described at a sufficient level of detail to permit a meaningful comparison with the proposed concept. AECL should also establish a method of evaluating each alternative that indicates the relative importance of social, economic and environmental criteria in judging the acceptability of each concept. If sufficient information on an alternative disposal concept is not available, AECL should present the basic principles and inferred impacts of the alternative, and provide a rationale for not developing that alternative concept further.

2.2 The AECL concept of nuclear fuel disposal is based upon disposal in plutonic rocks at depths of 500 - 1,000 metres. It is assumed that the host rock would act as a barrier to radionuclide migration, would not contain commercially attractive minerals, would be geologically stable, would be capable of withstanding additional stresses resulting from the construction of the repository, and would have sufficient volume to accommodate the repository.

AECL must demonstrate that suitable sites exist within the Canadian Shield that meet all geological criteria for the safe disposal of high-level radioactive waste.

2.3 In the work to date on the Underground Research Laboratory (URL) and at Atikokan, Chalk River and East Bull Lake, there is an implicit assumption that these research sites are representative respectively of plutons, gneisses and gabbros throughout the Canadian Shield. In the specific case of the

URL, it is possible that its location in the Lac du Bonnet batholith close to the boundary of the Shield may have given it a fluid or stress history quite different from plutons in the interior of the Shield.

AECL should justify the use of the Lac du Bonnet batholith, and other areas investigated, as models for rock masses throughout the Canadian Shield.

2.4 The proposed disposal concept is based on the assertion that, although there will be some escape of radioactive and chemical contamination sometime during the post-closure phase, it will be insignificant in terms of environmental effect. This type of assertion, without consideration of uncontrolled or unforeseen events (including low probability events of significant consequence) may be unrealistic. Events which could occur over that time include:

a) seismic disturbance of the vault, including displacement by faults,

b) unintentional drilling into the vault,

c) explosive or intrusive volcanism,

d) global warming and the associated stresses on the repository,

e) meteorite impact, and

f) continental glaciation.

The Atomic Energy Control Board's Regulatory Document R-104 states:

> "The period for demonstrating compliance with the individual risk requirements using predictive mathematical models need not exceed 10,000 years. Where predicted risks do not peak before 10,000 years, there must be reasoned arguments that beyond 10,000 years the rate of radionuclide release to the environment will not suddenly and dramatically increase, and acute radiological risks will

not be encountered by individuals."

It is therefore incumbent on the proponent to demonstrate that predicted risks will peak within the 10,000-year upper bound established by the AECB. The selection of the upper bound also needs to be fully rationalised.

AECL must demonstrate that the effects from the risks they predict will peak before the upper bound of 10,000 years. Failing this, they should extend the mathematical modelling for a period with a more appropriate upper bound.

AECL must also evaluate low-probability events of significant consequence over the long-term life of the wastes and demonstrate their effect upon the repository. The EIS must include an assessment of the impacts on all environmental compartments due to the potential release of radioactivity resulting from the burial of high-level wastes. The assessments should take into account all of the above catastrophic scenarios that might induce slow, long-term seepage of radioactivity or a larger one-time discharge. The assessments also need to consider the various routes by which the releases could reach different environmental compartments, and how the use of these routes could be prevented or minimized. Events which are considered by the proponent to be of low probability and consequence should be listed, with an explanation for them being discarded from further analysis.

2.5 Many engineered materials are to be used in ensuring that the repository performs as designed. The long-term availability of these materials or alternatives must be verified.

AECL should identify and document the supply of critical materials (titanium, grouts, buffers, etc.) to be used in the construction and operation of the repository. AECL should present plans for coping with the unavailability of these materials during construction or operation phases.

2.6 The disposal concept being proposed involves a wide range of physical, chemical, radiological, biological, economic and social processes. Many of these can be treated separately, however, significant combinations of these individual processes can occur. Such combinations are referred to as coupled processes. For example, the heat given off by the

spent fuel could affect groundwater circulation and chemical reaction rates. Often coupled processes are recognized in the "hard science" or engineering areas, but the degree to which these are coupled to ecological, social and economic areas must also be addressed. For instance, poor communication of complex technical issues could result in public pressure to focus technical efforts on areas where they might otherwise not be justified.

The proponent must recognize the significant coupled processes and the nature of the coupling that exists throughout the whole concept. In areas where the coupling is non-linear, this must be identified and the magnitude of the effect must be discussed.

2.7 AECL is seeking approval for a concept to dispose of its own wastes and those produced by Canadian electrical utilities which generate nuclear power. When considering the management of nuclear wastes, the past performance of waste handling and storage facilities operated by Canadian industry and nuclear waste producers in other countries is germane and can provide valuable experience and guidance in selecting options for Canadian nuclear waste disposal. Documented experience is not readily available for the performance of used fuel storage bays at generating stations at Pickering or Bruce (Ontario), Gentilly (Quebec), and Point Lepreau (New Brunswick), or for waste storage facilities at Chalk River (Ontario), or Pinawa (Manitoba). In the U.S., as in other countries, nuclear waste facilities have leaked and contaminated groundwater, soils and surface water. The past performance of the nuclear industry in managing its nuclear waste is relevant when assessing long term management and disposal options.

AECL and Ontario Hydro should provide information on past practices and performances of the management of nuclear waste. This should include information on all spent fuel storage bays at nuclear power stations, and all nuclear waste storage facilities in Canada. Incidences of containment failures and subsequent environmental contamination in Canada and elsewhere should be reported. Experience with various containment designs and materials of construction should be documented. The proponent should evaluate the information gathered and ensure it is applied to the proposed waste disposal concept.

3.0 WASTE PRODUCTION AND STORAGE

3.1 The volume, type and the place of generation of wastes to be disposed of must be established, since each of these factors influences the characteristics of the disposal concept. For example, the volume of high-level waste will determine the size of the disposal facility. The type of waste (just spent fuel or all high-level wastes) will also influence the concept (disposal techniques, containers, facility layout, etc.). The origin of the waste will introduce yet another variable in the process.

The disposal of all high-level nuclear wastes associated with the research, development, demonstration, operation and decommissioning of Canadian nuclear power facilities should be examined.

The proponent should provide data for all past and projected high-level nuclear wastes, including waste storage locations, types, quantities, and physical, chemical and radioactive characteristics. A range of projected waste types and amounts should be presented to cover various nuclear power generation and station decommissioning scenarios. This should include projections based on the use of nuclear energy for heating, rather than only for electrical energy generation. Heating may occur on a broader geographical scale than electricity generation.

The EIS should clearly identify the existing types, sources and volumes of radioactive wastes from nuclear power facilities (and estimates of future types, sources and volumes) that are intended for deep geological disposal, or could come to be considered for such disposal in the future.

3.2 It is important that consideration be given to the possibility that waste forms other than used nuclear fuel (see section 3.1) may be transported to a disposal site. Plans for cask development or use of present casks need to take into account projected shapes, volumes, age and radioactivity, and thermal characteristics of other waste forms which may need to be transported. Such considerations must be included in a comprehensive program of cask development. Similar considerations apply to the design of the disposal containers.

AECL should indicate what flexibility provisions are being built into the conceptual design to ensure that wastes of different types can be transported, handled and disposed of safely. In particular, the casks need to be re-evaluated for suitability to carry all waste forms which may be transported to a disposal site, and the proposed container for spent fuel may have to be modified or redesigned to accept other waste forms.

3.3 With the many uncertainties associated with the proposed concept, the design of the primary waste containment is most important during the operational phase of the repository. AECL favours a relatively thin-walled titanium container for the used fuel bundles. Proponents in other countries have selected what might be more robust and conservative designs. A comparison of alternatives and the rationale for AECL's proposed design is relevant in the assessment of the concept.

AECL should provide details on alternative designs for the primary containment of nuclear wastes. Information should include the forms of wastes, the internal structure of the container, the construction materials for the container, etc., and the costs associated with the designs proposed by other countries and with alternative designs considered by AECL.

4.0 TRANSPORTATION

4.1 A reference transportation system should be developed to include such aspects as assumptions regarding waste form, cask types, fleet, anticipated frequency, size and number of shipments, system cost, mix of land and water transport modes, vehicle and ship (or barge) characteristics, potential routes, handling and support facilities, infrastructure requirements, operational considerations, emergency planning and institutional controls.

A reference, or so-called "base-case" transportation system would provide direction in the development of strategic and short-term planning by clarifying aspects of the program which need to be addressed. A strategic plan would demonstrate the sequence and interrelationships of planning initiatives which should be undertaken in the development of the system. For example, a cask development initiative should be undertaken only after all waste forms have been identified. Appropriate combinations of road, rail and water transport can be determined only after transportation facilities for each reactor and type of disposal site are examined. Routes can be determined only after a methodology for selection is agreed upon.

A clearly defined risk and environmental assessment program needs to be included in determining the transportation system configuration. Potential safety and environmental risks need to be determined for operations under normal and accident/incident scenarios. Risk parameters need to be outlined and performance measures defined. The nature of potential effects (i.e. socio-economic, environmental, cost) need to be determined for probable system configurations. Again, this would involve the development of assessment parameters and performance measures. After the completion of these risk and impact identification activities, compensation and/or mitigation processes should be outlined.

The strategic plan may also suggest opportunities for logical scheduling of public, governmental and contractor participation in the transportation planning process.

A reference (base-case) transportation system and a strategic plan should be developed by AECL and Ontario Hydro and presented in the EIS. For each component of the reference system, risk and impact parameters must be identified, and their potential effects assessed.

4.2 Recent research and experience in the U.S. and Europe has demonstrated that dual-purpose casks (for temporary storage and transportation) can be feasible within a transportation system. The use of such casks may be of great value in transportation system and facilities design, storage monitoring, operations and scheduling of shipments. Further, the flexibility provided by use of such casks would relieve pressure due to lack of reactor storage space should the siting and construction of any future repository be delayed.

The feasibility of designing and certifying a dual-purpose cask for storage and transportation should be investigated.

4.3 While the probability of a terrorist attack or an act of sabotage is low, the consequences of such actions may be catastrophic. Not all types of stresses on a cask which may be brought about by acts of sabotage or terrorism can be known, and engineers may be unable to design casks to withstand the use of techniques of sabotage and weaponry yet to be developed. Nevertheless, thought needs to be given to sabotage situations which may occur during cask fabrication, handling, transportation and transfer to a disposal site. A first step is the development of a quality assurance program for cask design, fabrication, testing and operations. Reasonable scenarios need to be developed and considered with actual and conceivable incidents of terrorism or sabotage in mind. Contingency plans for public information, emergency response and cask security must be developed for those cases which appear most probable. This is a matter of institutional control which must be considered to enhance the integrity of the transportation program.

A cask development program should include safeguards against possible acts of sabotage and terrorism.

5.0 SURFACE FACILITIES

5.1 Many activities involving the use of natural resources (water use, clay mining, rock stockpiling, diesel fuel, etc.) are associated with site preparation, site operation, and site closure. These activities, which may not be unique to waste disposal sites, can affect the local socioeconomic and natural environment. The effects of associated activities related to the disposal site should be considered in the biospheric assessment.

As an example, with respect to water use, there are a number of issues which need to be addressed. For instance, the purposes for which water will be needed, how much will be required during construction and operation, and the amounts and quality of groundwater predicted to seep into the preclosed vault over time should be estimated. A related issue which needs to be discussed is the collection, treatment, and disposal/release of wastewaters.

AECL should identify and investigate the environmental impacts of activities associated with the development and operation of the disposal site, and develop appropriate mitigation measures.

5.2 Should high-level radioactive wastes continue to be stored at the point of origin or should regional/national storage/disposal sites be adopted? The governments of Canada and Ontario have already made a commitment that AECL and Ontario Hydro would submit documents to enable the risks and benefits of single and multiple disposal sites to be evaluated.

AECL should conduct studies (including a cost-benefit analysis) to compare the establishment of one centralized storage or disposal site for high-level radioactive wastes with the establishment of several regional sites performing similar functions. Included in these studies should be a review of the transportation of the wastes from point of origin to regional or national storage/disposal sites. This must take account of factors such as the relative risks posed by a large number of small shipments versus a smaller number of larger shipments, and whether shipments should be direct from the source or through regional storage/bulking sites.

5.3 The transport of the heavy casks, used to house containers of spent fuel rods, provides opportunities for breaching the containment with punctures, abrasions, and other accidental surface exposures. This will result in areas on the container surfaces with the potential for premature corrosion or leaching that will require detection, evaluation and repair on receipt at the disposal facility.

AECL should indicate what container inspection procedures will be used, what criteria will be used to judge acceptability for disposal, and how unacceptable containers will be treated.

6.0 SUBSURFACE FACILITIES

6.1 High natural rock stresses have been measured by AECL at the Underground Research Laboratory (URL) at Pinawa, Manitoba. These stresses are indicative of potential rock spalling in the vault, and the creation of permeable zones which could potentially act as radionuclide migration pathways. This raises the question of whether such natural stresses, in conjunction with additional thermally-induced (man-made) stresses, could cause rockbursting or creep deformations which would jeopardize the integrity of containment. In addition to the high absolute values of rock stress, there is also evidence of large variations in their direction and magnitude due to geological structure, of the presence of anomalous stresses such that the measured vertical stresses exceed the weight of the overlying rock, and of stress ratios which are significantly higher than general experience indicates. All of these factors indicate that there will be considerable uncertainty in characterizing in-situ stresses at a candidate site.

In addition, the uncertainties inherent in predicting the distribution of excavation and thermally-induced stresses, in understanding the effects of various stress regimes on rock behaviour, and in quantifying the consequences of these effects, combine to create a general level of scientific uncertainty which must be addressed by appropriate engineered solutions and mitigating actions.

AECL must demonstrate their ability to measure and assess geomechanical effects of vault construction and operation. In addition they must demonstrate that they have addressed all pertinent issues of geomechanics by showing that all possible adverse consequences arising from geomechanical uncertainties can be explicitly addressed by engineered solutions throughout the design, construction, operation, and closure of any repository.

6.2 The integrity of the containers used to encase the high-level waste will be threatened by the corrosiveness of the high salinity groundwater, by dissolved gases and by microbial activity - conditions that are anticipated to be present throughout the Canadian Shield. Factors which define the radionuclide "source term", such as the rates of container

corrosion and spent fuel dissolution, must be determined for predictive radionuclide transport modelling. There are a number of related concerns that should be documented by AECL in their assessment:

a) a thorough review of container corrosion (Ti and Cu) over the expected environmental conditions of redox potential and salinity,

b) the redox and corrosion potential at the container surface due to radiolysis,

c) the coupling of heat and mass transport with radiolysis to determine what effect these have on the corrosion damage function,

d) the measurement of exchange current densities and transfer coefficients for the reduction of O_2 and H_2O_2 on Ti and Cu at temperatures up to 150°C,

e) the measurement of corrosion kinetic parameters for Ti and Cu in simulated near-field repository environments,

f) a thorough review of microbially-induced corrosion of Ti and Cu containers in the proposed repository, in particular the roles of oxygen and sulfides,

g) the development of models quantitatively describing the effects of redox and corrosion reactions on container behaviour and UO_2 dissolution, and

h) the justification of values chosen for all relevant parameters.

The EIS must address threats posed by microbially-induced corrosion, saline groundwaters and gases to the integrity of the waste containers. Furthermore, AECL must demonstrate that their conceptual design minimizes the failure rate of the containers.

6.3 The AECL waste disposal concept uses a bentonite-based buffer material as a sorptive barrier around the waste containers. The swelling and hydraulic properties of the bentonite deteriorate above 100° C. Thus, the effects of high temperatures as well as high salinity groundwaters on the

physical and chemical properties of the buffer, backfill and sealants are of concern, as there is reason to fear a deterioration in some of the properties for which they were chosen. Consideration should also be given to the use of other materials (zeolite, illite) in view of bentonite degradation at prevailing vault conditions (groundwater salinity and elevated temperature). Finally, consideration must be given to the method of buffer and backfill emplacement so that the buffer and backfill are sufficiently tightly packed as to not allow any high-permeability pathways to the geosphere.

AECL should justify the proposed buffer, backfill and sealant materials, and their methods of emplacement, in terms of their ability to retain escaped radionuclides at post-emplacement temperatures which must be explicitly substantiated. They should demonstrate that the expected saline subsurface conditions and the anticipated microbial activity do not jeopardize the functioning of the buffer, backfill and sealant barriers.

6.4 Should leaching of the spent fuel occur, an understanding of the physical-chemical nature of any leached radionuclides in colloid, solute and gas phases will be important in determining their fate and transport. Salinity and elevated temperature are two geochemical issues of special concern with respect to the ability of the buffer, backfill and sealant materials to retain any escaped radionuclides. AECL must demonstrate their ability to characterize the speciation of radionuclides in the groundwater or brine, and the sorption of radionuclides on the buffer, backfill and sealant materials under saline and high temperature conditions.

AECL must determine, for the full suite of radionuclides that might be leached from a failed container, the nature of their interaction with brine and with the buffer, backfill and sealant materials at various temperatures and ionic strengths so that the transport and fate of the radionuclides can be accurately predicted within the vault.

6.5 Gas buildup in the vault may occur as a result of degassing of groundwaters liberating methane and nitrogen, container corrosion producing hydrogen, gamma radiolysis of water releasing hydrogen or microbially-mediated decomposition of

organic solutes. The gas may create elevated pressures within the repository and could greatly complicate the understanding of radionuclide migration within the vault and surrounding environment through the creation of a second phase and the loss of transmissivity through the accumulation of gas by-products. Moreover, for the performance assessment flow modelling, an understanding of all gas phases will be required.

AECL must determine the nature of the gases and the rates of gas generation and accumulation that may occur within the vault over the long-term life of the wastes, and the effect that any gas phase will have on radionuclide transport. Safeguards against pressurization of the vault through gas accumulation should also be discussed.

6.6 The thermal load caused by the high-level radioactive wastes will create complex couplings of hydraulic, geochemical and geomechanical processes in the vicinity of the repository. In order to evaluate these processes, it will be necessary to conduct coupled deterministic modelling involving thermal-hydraulic, thermal-geochemical, and thermal-mechanical effects to evaluate their effects on groundwater flow systems in fractured crystalline rock. Of particular interest is the potential for induced fracturing in terms of stress-induced rockburst events triggered by increased stresses due to thermal loading at some time after waste emplacement. The potential for shear-slip mechanisms to be induced along existing discontinuities in the vicinity of the waste containers, thereby risking shear displacements which could increase permeability and potentially rupture a container, are events of special concern.

AECL must demonstrate to what extent the thermal load of the repository will alter both the near-field and far-field groundwater flow patterns in the more permeable fracture zones that form the most significant pathways in the groundwater flow system. In conjunction with these flow system studies, AECL should demonstrate to what extent the heat flux from the waste could affect all geomechanical and geochemical properties of the vault and surrounding rock.

6.7 The vault models assume that microbial activity will not significantly influence radionuclide transport. Radiation-induced mutation and selection might result in radiation-resistant mutant microorganisms which could possess enhanced or novel activity. Mutant activity could change the vault geochemistry at a greater rate than currently predicted.

AECL should indicate the likelihood of microbial mutation/evolution which could potentially alter or enhance microbial effects on radionuclide release, subsurface transport, or input to the biosphere.

6.8 If not properly sealed following waste emplacement, exploration boreholes and repository shafts could provide migration pathways for leachates from the vault to the biosphere. The corrosive environment under which the sealants will have to perform over the long-term life of the wastes will stress the properties of these materials. The evaluation of grouting and sealing technologies must consider long-term performance under the influence of transient temperature and pressure in the rock as created by thermal loading from the waste materials and redistribution of stress fields, and attack by brine fluids. In addition, the assessment of long-term effects must include consideration of microcrack initiation and growth, which appears to continue for an indefinite time in highly stressed regions. Because fracture grouting and shaft sealing experiments are not to take place at the URL until 1993-2000, there is some doubt as to the ability of AECL to predict the effect of elevated salinity, pressure and temperature upon the integrity of the grouting and sealing materials.

AECL must demonstrate the ability to seal underground openings and rock fractures over the long-term for conditions of elevated salinity, temperature and pressure.

6.9 Natural analogues are being used increasingly to justify the integrity of proposed underground disposal systems for high-level radioactive wastes. In Canada, studies have been conducted by AECL on the Cigar Lake uranium deposit. Natural analogues have also been examined under international sponsorship (e.g. Oklo phenomenon in Gabon, Koongarra uranium deposit in Australia). In using analogues to make assertions of safety regarding the burial of high-level radioactive

wastes, it is important that all significant similarities and differences between the analogue and the repository be considered and presented, so as to suitably qualify the conclusions which are being advanced. For example, while useful inferences can be made, a natural uranium deposit within a sequence of water-bearing sedimentary sandstones cannot be directly compared with a repository for high-level nuclear waste which is to be located in fractured igneous rock.

AECL should present a rigorous and objective evaluation of the use of natural analogues to verify geological disposal concepts, and should then employ natural analogue studies in a rational manner to assess the proposed concept. In doing so it will be necessary to properly relate the physical/chemical settings and properties of the analogues to those of the proposed repository.

7.0 GEOSPHERE

7.1 Groundwater flow in plutonic rocks will occur predominantly in any large scale interconnected fracture systems and faults that exist. These flow paths can serve as transport routes for radionuclides dissolved or colloidally suspended in the groundwater. Fractures and joints formed as a result of the excavation of the vault may open transmissive pathways from the vault horizon to an existing fracture system and then to the biosphere. Of special concern are vertical fractures since they likely represent the most important potential pathways from the repository to the biosphere. Dykes, sills and other crosscutting features may provide additional pathways. Studies at the URL have shown that the in-situ stress regime and the mechanical properties of the rock are also strongly influenced by proximity to, and the nature of, major fracture zones. The geochemical properties of major fracture zones need to be established. This requires the characterization of not only the fracture surface mineralogy and surface contact area but also the geochemical evolution of the fracture fluids as they move from the repository horizon. Thus characterization of fracture zones is required for hydrogeological, geochemical and geomechanical reasons.

Because AECL's ability to identify and characterize fractures and fault zones is crucial to the evaluation of a potential repository site and the ultimate selection of a site, AECL must demonstrate their capability to identify and locate all fracture pathways that significantly influence the groundwater flow pattern, and to characterize them on the basis of their hydrogeologic, geochemical and geomechanical properties.

7.2 It is imperative that AECL demonstrate a sound understanding of the nature of groundwater flow systems in the plutonic rocks of the Canadian Shield during the concept assessment stage of their program, and that they develop and demonstrate a methodology that will be successful in assessing the groundwater flow systems at an actual repository site. AECL should also address the question of how they plan to include the effects of small-scale geological controls in their large-scale assessments of groundwater flow. Furthermore, AECL must document how they propose to deal with the issue of potential changes in hydrogeologic conditions over the long-term life of the wastes. During site characterization, the

hydrogeology of the host rock will be studied in detail, providing input to pathway analysis in the geosphere model of AECL's system validation code (SYVAC). However, what is the degree of confidence that can be placed in extrapolating what we characterize in detail today, over the lifetime of the wastes? How much change can be expected in the patterns of flow on that time scale, due solely to a slow evolution of the system, without perturbation due to glaciation or climatic change?

AECL must demonstrate that they are capable of defining groundwater flow systems in plutonic rocks, including the identification of the depth of active fresh water circulation, the lateral extent of local flow systems and the presence of various groundwater discharge zones. Furthermore, AECL must document how they propose to assess the magnitude and likelihood of potential changes in hydrogeologic conditions over the long-term life of the wastes that arise from the slow evolution of flow system characteristics over geologic time scales, and due to potential events such as continental glaciation and global warming.

7.3 In the site characterization plan for the U.S. high-level radioactive waste disposal program, considerable weight is given to the assessment of the groundwater travel time from the repository to the biosphere, estimated prior to waste emplacement. This parameter is meant to provide a means with which to evaluate (1) the suitability of the hydrogeologic setting for a high-level waste repository, (2) probable groundwater pathways and discharge points, and (3) the uncertainty in defining the nature of the flow system.

AECL should indicate how they will quantify groundwater travel times from a proposed repository to the biosphere.

7.4 A rigorous characterization of the physical-chemical properties of the critical radionuclides and the hydrogeochemical properties of the groundwater flow system is required to achieve a satisfactory understanding of the transport mechanisms. Reliable predictions of radionuclide transport require knowledge of the surface contact area between the transported solute and the rock mass, the aqueous surface chemistry of the fractures with respect to critical radioelements (e.g. I and Tc) and the role of microbial

processes in the fracture systems. Furthermore, it will be necessary to document the abundance and mobility of natural colloidal material in the groundwaters of plutonic rocks, the propensity of radionuclides to form colloids and the sorptive capacity of natural colloids for radionuclides. Also, complete characterization will require measurement of the complexing capacity of groundwaters for critical radionuclides. Finally, it is necessary that AECL demonstrate that matrix diffusion and sorption processes do significantly retard radionuclide solute transport in fractured plutonic rock as assumed in AECL computer simulations.

AECL must indicate how they will determine reliable values for the principal geochemical parameters controlling radionuclide transport in the fracture systems, including the effective contact area between transported solutes and the fracture surfaces, sorption coefficients for critical radionuclides, complexing capacity and colloidal charge density. In addition, AECL should indicate the ways in which they will assess the levels of confidence and uncertainty in these key parameters. In order to demonstrate the viability of the geological barrier, AECL must prove that matrix diffusion and sorption processes significantly retard radionuclides during solute transport in fractured rock.

7.5 The selection of plutonic rocks over other rock types was in part based on the assumption that groundwater flow in plutonic rock would be insignificant and therefore groundwater access to the waste would be limited. Given the uncertainty that exists in identifying permeable structural discontinuities in plutonic rock, and the recognition by AECL that actual conditions encountered during excavation will probably be different from conditions defined by exploratory boreholes, it seems possible that a permeable fault could intersect or be in close proximity to the vault. If this is the actual case or an assumed scenario for performance assessment, three concerns arise:

a) Has AECL selected a minimum containment period for the geologic barrier, and if so, what is it, and how was it established?

b) Does this likely case or assumed scenario provide comparable containment to other similar cases or scenarios for other rock types?

c) If engineering solutions (such as grouting, sealing of fracture zones, etc.) are required to achieve a minimum barrier requirement, has AECL successfully demonstrated such a capability?

AECL should assess the adequacy of the geologic barrier provided by plutonic rocks relative to other rock types using realistic values for groundwater flow and solute, gas and colloidal transport both with and without the assumed use of demonstrated fracture sealing technology.

7.6 There is insufficient information on the microbial community composition, biomass, activity, physiology and distribution in fractured crystalline rock to confidently rule out their influence on near surface transport of nuclides and other constituents. Further, there is little or no data on how microbial populations are influencing the geochemistry of groundwater in the fractures of crystalline rock.

AECL should describe the microbial activity (including that of oligotrophes) in the upper fractured zones of the plutons, and indicate whether the level and type of microbial activity there is sufficient to mobilize actinides and other hazardous compounds to the surface at a greater rate than currently anticipated.

The specific activities of the microbes and consortia of microbes in the exposure, transport, biocomplexing, volatilization, and leaching of radionuclides over the required long period of waste confinement need to be addressed. Any special precautions to minimize these microbial influences should be defined.

8.0 BIOSPHERE

8.1 The types and quantities of both radioactive and non-radioactive contaminants likely to arise from routine or accidental releases from the facility during pre- or post-closure must be identified. Their rates of movement through environmental pathways and sinks, and their effects on local and regional populations of non-human biota must be evaluated. A number of non-radioactive metals have stochastic health effects, and risk conversion factors for human populations have been established by the U.S. Environmental Protection Agency (e.g. daily intake of X corresponds to a cancer risk of Y). Use of this type of risk approach for non-human populations may be useful, since it permits consideration of additivity. It does not, however, preclude the concurrent use of standard threshold concentration criteria for various biota, which are designed for ecosystem protection, and which typically ignore the additive effects of multiple contaminants.

AECL should describe how food chain and other contributions to radiological dose and non-radiological contaminant intake for biota are considered in pre- and post-closure risk evaluation of both normal and accident scenarios. Similarly, the proposed use of radiological dose and threshold concentrations for biota should be explained and justified. The concept assessment documents should link environmental concentrations with population, community, and larger ecosystem dose and effect.

8.2 Ecosystem protection requires definition in terms of specific endpoints (e.g. population decline, loss of diversity). Often, assessments do not address ecosystem protection except to suggest that regulatory dose limits designed for human protection will automatically protect the ecosystem. There is support for this statement; there is also contrary evidence. Ultimately, ecosystem protection may depend on what it is that we value about the ecosystem and how much change we are willing to accept.

Once ecological endpoints of concern are defined, and baseline status measured, a prediction of long-term impact on these endpoints will be required. There are currently large uncertainties associated with mechanistic models of ecosystem

function, and it may be premature to utilize such models, but radiological and non-radiological exposures of various ecosystem compartments must be estimated and compared to known ecosystem effect levels.

AECL should define, for both pre- and post-closure ecosystem protection, what and how ecological endpoints of radiological and non-radiological contaminant exposure would be measured and predicted, what degree of certainty is associated with the predictions, what degree of change from baseline conditions might be considered acceptable for protection of species other than humans over a specified spatial domain and timeframe, and how predictions are substantiated regarding the likelihood of such ecological changes.

8.3 The concept assessment of the "reference environments" must be as complete as practical, and must be defined in sufficient detail to evaluate detrimental ecological effects in any ecoregion in which a disposal facility may be located. Although not all ecosystem components need to be included in the reference environments, the reasons for inclusion or exclusion of each component must be documented. In any given ecosystem, (from the northern boreal forests to the more southern areas of Ontario) some components are more sensitive to perturbations (i.e. less stable) or less resilient (in recovering from disturbances) than others. The reference environments should include considerations of aquatic and terrestrial ecosystems each with sensitive or unique components (such as an endangered species or a fragile habitat) to ensure these assessments cover as wide a range of ecological components as possible. In addition, these reference environments should emphasize emergent properties of the communities or ecosystems (e.g. diversity, stability, resilience) without ignoring individual species, guilds, or functional feeding groups. During concept evaluation, potential biophysical impacts (e.g. ground temperature increase due to thermal energy produced by the stored wastes) have to be incorporated into an interpretation of possible biospheric impacts of the waste disposal facility.

AECL should evaluate a series of "reference environments" that represent the range encountered in geographic regions being considered as potential disposal facility locations. For each of the reference environments, AECL should justify the

ecosystem components included and excluded, and explain the reasoning for each component's status. Provisions for including unique or critical species or habitats should be explained, and the definitions of the ecological properties to be examined must be clearly specified. Evaluation of the reference environments must include the physical (e.g. thermal and hydrologic) and chemical (e.g. energy and nutrient flow) components in addition to the biotic communities of each ecosystem.

8.4 Generic parameter values have been developed by international organizations for use in environmental transport and assessment models. However, these values are usually considered default values, and it is always recommended that site-specific values be used, wherever possible.

AECL should be required to develop site-specific parameter values for reference environments referred to in the biospheric assessment models. Site-specific parameter values should be developed either from reliable environmental data that are currently available or from data obtained from laboratory or field experiments.

8.5 Microorganisms can transform some metallic compounds such that they become volatile. For example, mercury is methylated to form methyl mercury, a very volatile compound. Formation of gaseous by-products will influence the transport of radionuclides in groundwater (reduction in sorption, increased penetration through small fractures). Further, microbially-induced changes in the forms of the radionuclides may influence predominant migration and uptake mechanisms (e.g. formation of a volatile product may increase the rate of environmental dispersion, and make inhalation a more important exposure mechanism).

AECL should indicate what microbial conversions of materials released from the facility could occur (e.g. methylation) which may change the form in which the materials enter the biosphere, and whether the form of the radionuclide or toxic chemical will affect how it enters and is distributed (e.g. uptake, gut-blood or lung-blood transfer) in the biosphere.

8.6 Microorganisms are responsible in some instances for establishing redox, pH and other controlling variables in sediment and shallow groundwater. The mobility and state of some substances (both stable and radioactive) will be affected by these variables. If a groundwater discharge zone is anaerobic, some substances may be immobilized and, over time, they may become concentrated. Concentration of certain materials may cause microbial death or inhibition of microbial activity because of toxicity effects. This may result in a change in the controlling variables, which may in turn result in the remobilization of certain substances (e.g. aerobic conditions established because oxygen scavenging microorganisms are inhibited). Redox-induced immobilization could thus control the predominant radionuclide "sinks". The sinks could later change to sources which would serve as pools from which radionuclides could move into the biosphere and enter the food chain causing unacceptable effects.

AECL should indicate how microbially-induced controlling variable conditions will affect entry of stable and radioactive substances into the biosphere either directly (e.g. solubility, mobility) or indirectly through changes in the predominant microbial activity at a discharge zone, and whether the biosphere model has incorporated the role of biologically mediated controlling variables in evaluating transport routes through, and sources and sinks within, the biosphere.

9.0 SOCIAL ISSUES AND PUBLIC PARTICIPATION

9.1 The EIS to be prepared by AECL will be based on over ten years of research and development on the nuclear fuel waste management and disposal concept. The magnitude, detail, scope and complexity of the EIS will be such that adequate review time must be made available to both the Panel and the intervenors. In order that members of the public have an opportunity to meaningfully participate in this environmental review, it will be necessary for participants to examine the existing documents which provide details of AECL's proposed concept, and other available documents which explain alternative concepts, and their environmental, social and economic benefits and costs. In developing guidelines for other environmental assessments involving large projects or policy issues, document review has required both a means of providing access to the relevant information and the allocation of sufficient time to allow for a review of the information.

The suggested review period of 2-6 months prior to the hearings may prove to be inadequate for a comprehensive review.

The proponent, either directly or through the Environmental Assessment Panel, should make available to participants a list of all research and development studies, and scientific and technical support documents used to prepare the EIS. The documents themselves should be part of the EIS review and should be available no later than six months prior to the submission of the EIS.

A minimum period of 8 months should be established to allow interested parties to review the completed EIS, prior to the start of the hearings.

9.2 Implementation plans for this project may change due to changing societal values and political will before construction begins. It is necessary at the concept stage for the proponent to outline the role that compensation for social or economic impacts (perceived and actual) will play in the siting process. Recent experiences with siting and implementation of large scale projects indicate that mitigation of, and compensation for, social impacts are

important parts of the siting process.

The proponent should outline its process for mitigating or compensating individuals and communities before or after closure as part of the siting process presented in the concept EIS. Further the proponent should indicate the ways in which compensation will be used as a means of choosing among a number of candidate sites.

9.3 It is recognized that the EARP concept review will not be considering the selection of an actual disposal site. However, the proponent should provide information regarding the siting process that could be used should the concept be found acceptable. The information should include the recommended approach to siting. For example, should it be an open and public process? Should it be based on a voluntary process such as that being used in Ontario by the Siting Task Force on Low-Level Radioactive Waste Management? Should it be based on a positive approach where the proponent attempts to prove a site is acceptable, or a negative approach where they show that certain sites are not suitable? To what degree should remote methods of site characterization be used as opposed to actual excavation of potential areas? The proponent must also indicate how surface-based (remote) testing and in-situ testing can be integrated to characterize sites. The real and perceived risks associated with various types of potential sites should also be evaluated.

AECL should indicate the methods (technical and social) it intends to use to identify available sites, and the criteria for selecting candidate sites. The proponent should indicate the methods to be used in estimating the environmental, health and social impacts, and risks at the various types of potentially suitable sites, and outline the process it will use to evaluate the alternative sites.

9.4 Because the concept review will not be site-specific, the effects on individuals, communities and social systems will be approximated by examining potential effects on broad geographical areas which are assumed to have some social and economic consistency. It is also clear that the central and the northerly of the three reference environments, which are key candidate areas because of their remoteness, include a number of native communities with differing views of northern

development and differing cultural and social responses to nuclear waste and social or economic issues. It is evident in the experience of other federal and provincial projects sited in similar locations that the cultural responses to government projects have varied substantially by location, and that the responses of native communities to the social and economic impacts of development have also differed considerably among communities.

AECL should provide a method of examining social and cultural responses to nuclear waste disposal in reference environments, and a method of assessing the differences in impact among native communities given their size and stability in response to social and economic changes.

9.5 The proposed concept focuses on hypothetical community social impacts in reference environments, and does not include a means of assessing the broader social system impacts of the concept. However, the EIS should also consider the broader impact of the concept on social systems, the social interactions and values of the Canadian population at large.

The EIS should clearly identify a means of assessing the broad social impacts of the concept, including the social acceptability to Canadians of permanent unsupervised disposal of high-level radioactive wastes as compared to storage options.

9.6 The present process for social impact prediction in the reference environments considered by AECL relies substantially on economic performance measures (input/output analysis, employment and gross national product change) as indicators of regional socio-economic effects. Such measures will likely produce positive economic impacts given the limited economies in the regions being considered, and the large flows of money and personnel required to construct and operate the facility, particularly when estimated over the proposed life of the facility. The facility will, nevertheless, impose economic and social costs on the environments considered, including social and economic costs of a non-indigenous workforce, changes in the local economy, particularly if a subsistence economy is affected, and social effects of a change in the composition of the population, particularly the effects on native communities including loss of traditional ways of life,

social disruption and changes in local values and patterns of interaction.

The EIS should specify the methods to be used to estimate the social costs of the concept so that they can be compared with the conventional economic benefit measures. AECL should be required to estimate the economic and social effects of the disposal concept in terms of the degree of change from existing economic and social patterns, as well as by the conventional measures of economic performance. Further, the EIS should indicate, in its evaluation method, what relative importance will be attached to economic and social change, versus conventional economic performance measures.

9.7 The question of nuclear waste disposal has been debated in other countries and has involved public inputs in the siting process and policy decisions. It should be clear from the procedures established in this particular environmental assessment review, that the ability of Canadians to participate in the decisions is equal to the best opportunities afforded to participants in other jurisdictions, and that Canadians do not have less opportunity to participate than citizens of other countries.

AECL should be instructed to review the public participation opportunities in other jurisdictions, and to document the extent to which the federal environmental assessment procedures for this review are comparable to processes for public input elsewhere, including the opportunity to participate in the discussion of the effects of the disposal concept on social values, energy policies, long-term environmental quality, and acceptable risk.

9.8 In the concept review phase, AECL proposes to identify safety criteria for the disposal facility. The development of safety criteria raises the question of what constitutes an acceptable risk. Individuals and communities are not uniform in their acceptance of risk. Some communities and cultures are more risk-averse than others. Ideally, a risk is acceptable if it is voluntarily borne by the population exposed to it. Voluntary acceptance suggests a process for determining the public acceptability to risk in any affected population.

The EIS should be required to establish the existing national public acceptability of risk from the disposal concept in its public consultation program. It should also be required to address the issue of regional and local variation in risk acceptance within and among various reference environments through public discussion and other viable methods, and it should indicate, in the evaluation of all assessments of risk and risk acceptability, how general levels of conventionally acceptable risk and public risk acceptance should affect the choice of the proposed disposal concept or some other alternative concept.

9.9 The EIS for the proposed high-level radioactive waste disposal concept will require an assessment of public responses to the concept on a society-wide basis. The views of the majority of Canadians (both the views of those who might be affected directly, and others) should be part of the concept review. The present process for obtaining a societal response to the concept involves public open houses and scoping meetings in major cities, written notices in newspapers, and a mailed newsletter from the Environmental Assessment Review Panel.

Those who are likely to learn about the proposed concept, and are likely to participate in the process, are a small and unrepresentative sample of the Canadian population geographically, culturally, and socially. To solicit a broad societal response to the concept, the public participation part of the process should include presenting the proposed concept in national electronic media: radio and television. Announcing and identifying the concept in terms of its rationale, the need for the project, the alternatives to the project, and some explanation of the siting process that may follow a decision about the concept, would reasonably allow for a Canada-wide response to the proposed concept.

AECL should provide, as part of the public participation process for a national audience, a means of identifying and describing the concept, its rationale, the need for the facility, alternatives to the concept, and an explanation of the siting process to be followed. AECL should also provide a means for responses to be collected, and for those issues and concerns raised to be assessed and incorporated into the environmental impact statement.

10.0 ECONOMICS AND FINANCING

10.1 The overall costs of building and operating a high-level radioactive waste disposal facility must be put into perspective. The existing high-level wastes currently in storage at reactor sites demand some type of long-term disposal; however, a question that must be addressed is how much the incremental costs of such a facility add to the marginal costs of nuclear generation.

AECL should be required to produce estimates of the costs of siting, construction, operation and closure of a high-level radioactive waste disposal facility.

10.2 AECL and Ontario Hydro should be required to present, in current dollars, cost estimates for implementing the proposed disposal concept, and all other options. These estimates should include (i) total costs and (ii) cost per unit of waste fuel, and indicate how these costs have been determined. The estimates should be presented in sufficient detail to allow the reader to relate cost estimates to the elements and operations of the concept. More specifically:

a) What is the time-pattern of the expected expenditures, and what data or assumptions underlie this projection?

b) How have expected increases in the real cost of elements of the concept been dealt with?

c) On what pattern of expected usage of nuclear-generated electrical energy are these estimates based? What assumptions have been made re nuclear versus non-nuclear generation in the future?

d) How sensitive is the cost per unit of waste fuel to the forecast nuclear energy usage?

e) Identify the sources and characteristics of the data on which estimates are based, and any limitations in the data.

f) Identify all assumptions that could be expected to have a material effect on the cost estimates.

g) Identify cost estimates which are based on an allocation (of either actual past costs or expected future expenditures) between the nuclear waste disposal concept and other activities of AECL or Ontario Hydro, and the basis on which the allocations were made.

h) Identify the factors to which the cost estimates are sensitive, and indicate the degree of sensitivity. "Factors" here should include not only estimates and assumptions, but also such things as the availability of material, skilled labour and technological advances.

i) With respect to the proposed permanent disposal concept, distinguish among at least the following costs:

- waste fuel storage (storage facility construction and operation);
- transportation, from generation to storage site, from storage to disposal site;
- site identification and characterization;
- disposal site preparation, roads, services, acquiring of leases on land, provision of residences and supporting community services;
- shaft, vault, underground transport, contingency systems - construction costs, maintenance costs;
- containers - cost, transport, storage;
- container emplacement (drilling, buffer, backfilling);
- facility sealing;
- facility and environmental monitoring;
- research and technology development;
- development and maintenance of contingency systems to deal with adverse effects, duplicate systems; and
- the costs of impact management, mitigation and mediation.

In order to use the standard methodologies for assessing economic impact (e.g. benefit-cost analysis, cost-effectiveness, cost-risk reduction, or macro-economic effects) complete and adequately detailed cost estimates for implementing the proposed disposal concept must be available.

10.3 Because of the long time periods involved in the development and implementation of the proposed disposal concept, it is necessary to have an idea of the financial plans associated with its implementation, specifically:

a) What is the time-pattern relationship between the cash flows required for implementing the disposal concept and the cash flow that would be required for the construction of additional nuclear generating facilities and/or the decommissioning of obsolete facilities? What would be the pattern and magnitude of these cash flows taken together?

b) What is the relationship between the time-pattern of expected cash collections and the expected pattern of cash out-flows for implementing the disposal concept? What is assumed regarding the investment of monies collected in advance? What is assumed regarding funds expended in advance of collections?

c) What is assumed concerning the source of funding for the concept? To the extent that funding is to come from current electrical energy users, how is the rate of collections to be calculated?

The proponent should be required to develop a plan to address how the permanent disposal facility, and all other options considered, would be financed.

10.4 The disposal concept cannot be viewed strictly from the point of view of either electrical energy producers or electricity users. It should be viewed from the point of view of a country which is currently committed to using nuclear energy and which is looking for a solution to managing high-level wastes.

AECL and Ontario Hydro should be required to explore the following matters:

a) **the fair and appropriate sharing of the cost of the disposal concept by all Canadians, all regions, users and non-users;**

b) **optimum size for a Canadian disposal facility, potential economies of scale, and the feasibility of reducing the**

cost to Canadians by disposing of high-level waste for other countries;

c) the potential impact of the adoption of the disposal concept on sales of the CANDU reactor (Will potential buyers expect Canada to accept the attendant spent fuel or other associated high-level waste?).

11.0 MODELLING AND QUALITY ASSURANCE/QUALITY CONTROL

11.1 A detailed quality assurance assessment of all predictive models used in the impact assessment should be conducted by AECL to ensure that their quality control procedures have been successful and that the model's predictions are reasonable. The verified quality of the numerical codes must be demonstrated through the use of structured programming, code documentation benchmarking, and archiving, amendment and evaluation procedures. Evaluation includes model verification and validation; both should be well documented. The evaluation of each model should include an assessment as to whether the model contains all of the appropriate physical and chemical processes and reasonable event scenarios (model examination); whether it is correctly coded to accurately solve the appropriate equations (model verification); whether the input parameters and procedures for determining parameter values are appropriate (data evaluation); sensitivity and uncertainty analyses; code comparisons; and model validation. Validation, which has been attempted through various international exercises (e.g. HYDROCOIN), involves comparison of predicted and measured values, and should be documented in the EIS. The field and laboratory data used in the verification and validation of each model must be shown to be correct and representative of actual conditions in the Canadian shield environment. AECL must be able to demonstrate that they have considered all coupled processes in the near field environment, and that they have also successfully simulated them using SYVAC.

AECL must demonstrate, in detail and in the most comprehensive manner possible, that all predictive models used have been sufficiently evaluated, verified and validated to prove useful in safety and environmental assessments of any proposed Canadian repository site.

11.2 The geosphere model in SYVAC will be based on equations that approximate the rock mass as an equivalent porous medium. However, it is not yet known at what scale it is possible to represent the transport process by an equivalent porous medium model. Some researchers have suggested that this may not be possible at any reasonable scale of interest. Demonstration of the validity of porous medium approximations for the fluid flow process does not necessarily imply that the same

approximation can be made for the transport process. Field experiments and numerical simulations suggest that solutes may be highly channelized within a network of interconnecting fractures. We do not yet have models that handle this channelling process at the field scale. Tracer experiments are planned at AECL's Underground Research Laboratory near Pinawa, Manitoba in the time frame from 1991-95, but it seems probable that these important experiments will lead at best to incremental understanding, rather than issue resolution. How will AECL demonstrate the acceptability of the disposal concept in light of the basic uncertainty in the nature and modelling of field-scale solute transport processes in fractured rock environments? Progress in resolving some fundamental questions is expected to lag behind the time frame for decisions on concept assessment.

AECL must demonstrate the adequacy of the models used to support the acceptability of the concept in spite of the present basic uncertainty in the nature and modelling of field-scale solute transport processes in fractured rock environments.

11.3 For reasons of analytical expediency in the system variability calculations, the geosphere model in SYVAC is based upon the identification of a series of one-dimensional flow paths for radionuclide migration. Advances in computing power suggest that one-dimensional approximations may no longer be a prerequisite for making these calculations.

AECL should demonstrate that the geosphere model in SYVAC, which is based upon identifying a series of one-dimensional flow paths for radionuclide migration, is able to adequately simulate both (1) the essential physics of three-dimensional solute migration at the field scale in a fractured granitic rock mass and (2) the complete range in possible solute behaviour.

11.4 The parameter values and probability density functions input to SYVAC have ostensibly been chosen to represent the reference environment and the range of environmental variation within the reference environment. Presumably, in site selection, these model inputs could be further refined, and uncertainties reduced by use of site-specific information.

AECL should identify parameters, distribution functions and uncertainties that will require reassessment, based on site specific data, after site selection.

11.5 Different models are proposed for risk evaluation during operation (pre-closure assessment) and following closure and sealing of the disposal facility (post-closure assessment). Nevertheless, these two models could or should have some common features. All differences in model structures and procedures need to be explained and rationalized.

The pre-closure pathways analysis model differs from the post-closure model in terms of model structure, parameter selection, data use, model verification, and quality assurance/quality control (QA/QC) procedures. AECL should be requested to clearly identify and explain these specific differences and the rationale for using different model structures for pre-closure and post-closure assessments.

11.6 Some of the assessment model predictions (post-closure) are for a period of 10,000 years, and it is physically impossible to validate or test model predictions for this length of time. One method of evaluating such model predictions is by model comparison (i.e. more than one modelling group performs independent calculations for the same scenario, and predictions, model structure, and parameter values, etc. are compared and evaluated).

For assessment scenarios where model predictions cannot be rigorously validated or tested, AECL should be required to have more than one modelling group provide independent predictions for model comparison and evaluation/reconciliation of the results.

11.7 Databases are amalgamated by various Canadian institutions for many purposes. As a result the inputs into these databases are not always consistent in units or in the quality of data. In addition, the data may have been collected for one purpose but used for other purposes, because they are the only data available. When several databases are merged to develop a database to provide parameters for assessment models, errors and inconsistencies can occur; thus, a quality control procedure should be developed to ensure the reliability,

accuracy, and suitability of the data obtained from other agencies.

AECL should demonstrate that they have developed a quality control program for their databases, both in-house and external data, that meets international standards for reliability, accuracy and traceability.

11.8 SYVAC is primarily a parameter uncertainty tool. However, process uncertainty also exists (e.g. solute transport mechanisms and approximations). In general, areas of process uncertainty, or controversy, should be identified, and this uncertainty incorporated into the overall risk calculations.

AECL should identify areas of process uncertainty, or controversy, and indicate how this uncertainty will be addressed in risk calculations.

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SCOPING MEETINGS FOR THE FEDERAL ENVIRONMENTAL ASSESSMENT PANEL REVIEW OF THE NUCLEAR FUEL WASTE MANAGEMENT AND DISPOSAL CONCEPT

SUBMISSION BY ENVIRONMENT CANADA

TECHNICAL APPENDIX

NOVEMBER 1990

Environment Canada Environnement Canada

This Technical Appendix has been prepared by Environment Canada's review team for the nuclear fuel waste management and disposal concept. Copies may be obtained by contacting:

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PREFACE

This Technical Appendix forms part of Environment Canada's written submission to the Federal Environmental Assessment Panel reviewing the Nuclear Fuel Waste Management and Disposal Concept. The Technical Appendix provides additional supporting information for many of the issues addressed in the main document.

The Technical Appendix follows the same numbering system for ease of cross-referencing with the main document.

ISSUES

1.0 GENERAL POLICY ISSUES

The original intent of the Nuclear Fuel Waste Management and Disposal Concept was the safe disposal of high-level spent nuclear fuel from both conventional once-through and, if adopted in the future in Canada, spent fuel reprocessing technologies. Because there are continuing technological developments in the nuclear power industry, including reprocessing of spent fuels, the general policy governing waste disposal options must be broad enough to encompass emerging technology. For example, because the nature of nuclear fuel waste and specific waste forms may, and probably will, undergo developmental changes with time, the Nuclear Fuel Waste Management and Disposal Concept may need to allow for secure, engineered surface storage of nuclear fuel waste as at least a temporary option.

Changes in the nuclear power industry will also be accompanied by changes in the technology surrounding nuclear fuel waste disposal. There have already been significant changes in waste disposal concepts over the time that nuclear reactors have been employed for power generation. Because the government and the nuclear power industry have been tasked to ensure safe disposition of nuclear fuel waste, there is an assumed responsibility to prudently apply "state-of-the-art" understanding tempered by the realization that future generations will bear some responsibility to redress present technical inadequacy.

It is essential that the EIS consider and evaluate not only all present nuclear fuel waste technology, but also prospective changes in nuclear power generation and in nuclear waste form. Also, because there is a certain unpredictability regarding future technological developments in nuclear power and nuclear fuel, the functional structure of the Nuclear Fuel Waste Management and Disposal Concept should be flexible enough to incorporate new technologies. The EIS should include a mechanism for developing contingency plans to deal with technological changes in the nuclear power industry. Likewise, these same principles should be applied to the technology for the safe disposal of nuclear fuel waste.

The following sections discuss some of these general policy issues in more detail.

1.1 Once-Through Versus Reprocessed Fuel

The CANDU nuclear reactors used for power generation operate using fuel elements made of unenriched uranium-oxide pellets. After the useful life of the fuel elements, the spent fuel elements are removed, grouped in bundles, and placed in short-term engineered surface storage to allow time for short-lived activation products to decay. The spent fuel bundles are what is now being considered for permanent disposal under the Nuclear Fuel Waste Management and Disposal Concept.

Most other countries use enriched uranium fuel to fuel the light-water reactors of their nuclear power industries. Several of these countries have developed facilities to reprocess spent fuel and to extract the "unburned" fissionable isotopes of uranium and plutonium and produce new reactor fuel rods. One potential environmental benefit of this reprocessing is that the reprocessing wastes principally contain shorter-lived radioisotopes which decay much more rapidly than the longer-lived fissionable isotopes, and consequently have to be contained for tens to thousands of years rather than tens to hundreds of thousands of years. Reprocessing is also beneficial from a resource perspective because less uranium will need to be mined to generate the same amount of electricity.

Present spent fuel reprocessing is a very expensive and may not offer any significant economic or environmental advantages to Canada at the present time. There is, however, a great deal of ongoing research in the international community to develop new approaches to reduce costs and reduce the environmental risks associated with reprocessing fuels. Although it is very difficult to predict when the overall net benefit equation for Canada will shift in favour of reprocessing, it is likely that it will occur during the lifetime of the proposed repository.

Although a decision to reprocess spent CANDU fuel may not be appropriate at the present time, the future for this technology in the Canadian nuclear fuel cycle should be conceptually evaluated in the EIS. The evaluation should be done not only on the basis of today's technology and economics, but also on the basis of those technologies which are conceptually feasible and may become technologically, economically, and environmentally attractive over the lifetime of the proposed repository.

1.2 Storage Versus Disposal

The development of reprocessing technology has broad implications for the disposal of nuclear fuel waste. If reprocessing becomes a part of Canada's nuclear fuel cycle, or a more global nuclear fuel cycle, consideration needs to be give to the future use of the Canadian nuclear waste repository. For example, if the Canadian nuclear fuel program will not consider reprocessing, then long-term secure monitored storage or permanent disposal should be evaluated. Including reprocessing technology in Canada's nuclear fuel cycle means that the Nuclear Fuel Waste Management and Disposal Concept must include both secure short-term engineered surface storage and long-term permanent disposal options for high-level reprocessing wastes.

Spent fuel wastes from CANDU reactors are presently being stored in both wet and dry storage areas at the sites of the respective nuclear power reactors, thus providing experience in secure short-term storage. The capacity of Canada's existing nuclear facilities to serve also as short to intermediate term storage facilities should be evaluated. The decision-making process regarding future short-term secure storage should be well documented, taking into account the process of public acceptance and engineering lead time involved in arriving at a revised version of the concept.

The engineering design considerations and critical analyses required for a "permanent" repository designed to ensure that no significant release occurs over a 10,000-year period are at the upward limit of current predictive abilities. From a purely environmental risk-benefit perspective, a secure storage option may be the most appropriate at the present time. This option would provide a greater degree of flexibility regarding future decisions such as those relating to reprocessing or other technological advances that may influence development of the Nuclear Fuel Waste Management and Disposal Concept.

1.3 Responsibility to Future Generations

Over the past several decades, society at large has become aware that past hazardous and nuclear waste management practices intended to provide for permanent disposal have not relieved future generations of responsibility for the safe disposition of these wastes. At the time, however, these waste disposal practices were considered to be "state-of-the-art" and condoned by regulatory agencies as being responsible and appropriate. Society is now

spending large sums of money recovering and treating wastes from these old hazardous and radioactive waste sites, and the general public is sceptical about present industry and government proposals to deal with wastes.

AECL must demonstrate sensitivity to society's wishes that the agency will avoid the mistakes of the past. AECL must instill public confidence in the process used to evaluate nuclear waste disposal technology The public must be assured that the society that today reaps the benefits of nuclear power does not pass the environmental and fiscal costs of these benefits to future generations.

1.4 Contingency Plans

As discussed briefly in Section 1.3, there is public scepticism in both Canadian and many other societies concerning the ability of scientists and engineers to provide permanent solutions for waste disposal, especially in areas such as the nuclear power industry where there is very little successful operational experience. Public scepticism is reinforced by the knowledge that the ideas and concepts we hold today are likely to change in the future, and these changes will undoubtedly result in future generations viewing our actions differently than we do now.

Given this general background, it is crucial that the EIS for the Nuclear Fuel Waste Management and Disposal Concept should address areas of uncertainty that may arise in the future, and provide contingency plans which will allow adaptation to changing conditions and societal norms. The EIS will gain public acceptance by instilling in the public the confidence that the concept contains the functional flexibility to deal with an uncertain future.

1.5 Ongoing Research and Concept Flexibility

The present concept assessment process is occurring long before the research and development studies at the Underground Research Laboratory (URL) are complete. These investigations include repository performance requirements such as those involving grouting and sealing, excavation effects on the host rock, tracer tests, and buffer and backfill emplacement. Some of these experiments may not be completed until after the year 2000, assuming that the requisite preliminary experiments are successful.

Thus, AECL is in the disadvantageous position of being unable to include in the EIS those experimental results that would appear to be essential in establishing that there is an acceptable level of confidence that the performance requirements established by the regulatory agencies will likely be met (AECB, R-71, p.4, 1985).

Because of the incompleteness of these experiments, the design of the permanent waste disposal vault and the nature of the waste disposal concept itself may well change as the results of the experiments at URL and other facilities are obtained. For example, results of experiments with the emplacement and functioning of the buffer and backfill may result in redesign of the emplacement room or the waste container. Also, if the economics of electric power production in the twenty-first century dictate a political decision to adopt fuel reprocessing and a mixed fuel cycle, the nuclear waste disposal concept would have to be changed from one of permanent disposal to one of either short-term engineered surface storage or long-term underground storage. AECL must demonstrate that the Nuclear Fuel Waste Management and Disposal Concept is sufficiently flexible to adapt to the results of ongoing or future research, either at the URL or in high-level radioactive waste management programs in other countries.

2.0 GENERAL TECHNICAL ISSUES

Given that Canada has a nuclear electricity generation program, there are high-level nuclear wastes that have been generated and will likely continue to be generated into the future. As discussed in the previous section, certain future policy decisions may affect the nature of these wastes (both physical form, and chemical and isotopic composition) which will, in turn, affect the manner in which they must be managed. It is important to recognize that there will likely be more than one option by which these wastes can be managed, and that, before a reasoned decision on the best option for Canada can be made, there must be an equivalent understanding of the alternative conceptual disposal options available.

Once a concept has been accepted, then the environmental assessment must clearly demonstrate that the concept is a viable one, and that the key elements related to siting and technological and social processes are available.

The concept assessment must also be balanced in terms of the level of effort (engineering, social and environmental) put into it to ensure that there is an overall optimization of costs expended versus environmental risk reduction obtained.

It is also important to realize that the concept will be evaluated in a number of disciplinary areas ranging from the more subjective social areas through the economic to the science, engineering and more broadly encompassing "environmental" issues. Within disciplines there are linkages, some of which may be independent and some coupled to greater or lesser degrees. Processes which are strongly coupled may be expected to have strong interactive linkages which may not be linear in nature. In these situations, consequence amplifications could occur and these must be carefully evaluated. In others, the linkages may be weak and dampening of effects may occur. An understanding of the linkages and the nature of the relationships is considered crucial.

2.1 Alternative Management and Disposal Concepts

The AECL concept of nuclear fuel waste management is based on geologic disposal in a mined repository constructed in plutonic rocks at reference depths of 500 - 1000 m (Boulton, 1978). However, plutonic rocks are only one of several geologic formations potentially suitable for disposal of high-level radioactive waste in Central Canada. Alternate geologic media initially considered

by AECL, but given a lower priority for evaluation included clay, shale, bedded salt and crystalline metamorphic rocks (e.g. gneisses) (Gillespi et al., 1984). The original decision to focus Canadian research efforts on plutonic rocks as the preferred host formation for radioactive waste disposal was taken early in the program in the mid to late 1970s.

Subsequently, AECL's research program showed that plutons had hydrogeologic, geochemical and geomechanical properties that were quite different from those assumed to exist at the time the decision was taken. Given this difference, it is reasonable to ask that the EIS should justify the continued preference of plutonic rocks over alternative geologic media in light of the results of the last 15 years of Canadian and international research. This requirement to evaluate the advantages and disadvantages to the environment of the proposed concept and alternatives to the proposed concept (i.e. alternate host media as well as alternate disposal methods) is appropriate and in fact consistent with established environmental assessment requirements in Ontario (Environmental Assessment Act RSO 1980 c140, s.5).

Over the past decade, there has been a broadly based international research effort aimed at investigating the feasibility of disposal of high-level nuclear wastes using a variety of technologies, including placing wastes in solar orbit, transmutation, deep-sea subduction-zone disposal and deep geologic disposal on continental land masses. The proponent should be required to review these alternative conceptual technologies to provide an overview of ongoing research related to the various disposal concepts, and to rationalize the deep plutonic rock disposal concept with the alternatives. (See Section 7 for a more complete discussion of disposal medium alternatives.)

2.2 Conceptual Site Versus Actual Sites

The characteristics of a geologically acceptable site have been defined by the AECB (R-72, pp.2-4, 1987):

1. The host rock and geological system should have properties such that their combined effect significantly retards the movement or release of radioactive material.
2. There should be little likelihood that the host rock will be exploited as a natural resource.
3. The repository should be located in a region that

is geologically stable and likely to remain stable.

4. Both the host rock and the geological system should be capable of withstanding stresses without significant structural deformation, fracturing or breach of the natural barriers.
5. The dimensions of the host rock should be such that the repository can be deep underground and well removed from geological discontinuities.

Some of these requirements will be easier to meet than others. For example, there is little doubt that, with the significant exception of the Ottawa Valley, the Canadian Shield in Ontario is "substantially aseismic" (Adams and Basham, 1989); thus, the third requirement of geological stability is not an onerous one for the proponent. In contrast, the lack of reported in-situ solute transport experiments and the high in-situ rock stresses measured at the URL suggest that the first and fourth requirements, as stated above, will need to be addressed in great detail if the concept is to receive widespread acceptance.

Therefore, it is important that the EIS demonstrate that there is a high probability that sites which meet the above criteria exist within the Canadian Shield and will be available for use by AECL.

2.3 Representativeness of the Research Areas

It is an implicit assumption of the choice of the research areas on the Canadian Shield that the principal rock types are representative of those across the Shield. Thus, it is assumed that the gneisses that comprise the Chalk River research area and the plutonic rocks of the Lac du Bonnet batholith (i.e. that in which the Underground Research Laboratory is constructed) are similar to those throughout the Shield.

However, geochemical evidence from sulphur isotope studies suggest otherwise. For example, there is evidence that formation waters from the Western Canadian sedimentary basin have invaded the Lac du Bonnet batholith (Purdy, 1988; Gascoyne et al., 1989). Similarly, Bottomley et al. (1990) concluded that the East Bull Lake gabbro-anorthosite pluton, another AECL research area, was invaded by saline formation waters from either surrounding Palaeozoic sedimentary rocks or nearby Proterozoic formations. Both the Lac du Bonnet batholith and the East Bull Lake pluton are situated at the edge of the Canadian Shield and have, therefore, been vulnerable to invasion of foreign formation fluids over time. The

long-term geochemical evolution of these fluids would be a function of water-rock interactions (see Section 7).

Thus, there is reason to question whether AECL's choice of its research areas is appropriate for characterizing the fluid and stress history of similar rocks across the Canadian Shield. It is recommended that AECL justify the selection of these research areas in the EIS.

2.4 Low-Probability High-Significance Events

Because of the nature of the probabilistic analysis by which the regulatory significance of the acceptability of a repository will be judged, events of very low probability of occurrence but of potentially great significance should not be omitted from the analysis. It is important that the general public understands that these events were considered along with their consequences and why, if they are not included, have they have not been.

2.5 Material Availability

The proposed repository concept may be expected to be operational for over 50 years, and perhaps 60 to 70 years, beyond the concept approval. Because certain crucial materials (e.g. titanium) upon which the successful implementation of the concept is based may become increasingly scarce with time, it is important that future supplies or acceptable substitutes be identified.

2.6 Coupled Process Linkages

Coupled processes may influence the transport of radionuclides and the resultant dose received by man within the biosphere. Geotechnical processes have perhaps the greatest potential for influencing local surface water dilution factors and resulting changes in the radiation dose received by man.

Some coupling effects may prove to be advantageous in some instances, and it may be desirable to enhance these effects. This is illustrated by the recent plans of the CSIRO Geomechanics Division to enhance the thermal advection of groundwater surrounding a deep repository. The scheme would involve the establishment of a natural self-contained loop for thermal convection that would provide heat dissipation from the waste and

prevent the build-up of excessive temperatures in the vault.

One set of negative biosphere-geosphere coupled processes relate to intrusion activities in which man, as a biosphere component, may accidentally drill into or deliberately attempt to extract "geothermal" heat from the vault anomaly. Coupled processes of this nature are expected to result in increased doses. The potential interaction between "coupled processes" and directions for further study of coupled processes are described in the following section.

Coupled Processes in the Geosphere and Vault

A number of coupled processes have been suggested by researchers in various fields as targets for further study because of their potential critical importance in the role of groundwater movement generally, and radionuclide transport from a deep high-level waste repository in particular. These include:

1. large-scale thermo-hydro-mechanical effects
2. colloid transport;
3. thermochemical interaction (precipitation/dissolution);
4. hydrothermal convection;
5. fracture filling/opening and channelled flow (de Marsily, 1987);
6. chemical-mechanical effects (Cook, 1987);
7. retrograde (thermal) precipitation and sealing of canisters; and
8. chemical barriers creating hydraulic seals (Langmuir, 1987).

The key issue involved in evaluating coupled processes in a practical time frame is priority identification. This means that there must be a rapid movement from the "discovery" stage to an "initial assessment" stage in identifying the critical processes which must be understood to produce an adequate safety assessment for a disposal scheme. If certain identified processes are subsequently ignored, the rationale for this should be presented. Alternatively, if resources are to be allocated to research into specific processes, this should also be rationalized in terms of initial assessment results.

TABLE 2.6.1: COUPLED PROCESSES AND EXAMPLES OF THEIR EFFECTS (adapted from Tsang, 1987)

Interaction**	Example of Effect
T —— H	Temperature Increase → Thermal Convection
H —— T	Increased Flow → Temperature Redistribution
T —— M	Temperature Increase → Thermal Fracturing
M ····· T*	Faulting → Thermal Friction
T —— C	Temperature Increase → Increased Solubility
C ····· T*	Endothermal Reaction → Temperature Decrease
H —— C	Nuclide Migration (Advection) → Precipitation/ Adsorption
C —— H	Precipitation (Fracture Infilling) → Reduced Flow
H —— M	Increase Pressure → Hydraulic Fracturing
M —— H	Faulting → Increased Flow
C ····· M*	Phase Change (Decrease Density) → Fracturing
M ····· C*	Increase Stress → Chemical Corrosion
T —— H	Chemical reactions and nuclide transport in fractures across thermal and hydraulic gradients

* Denotes weak effects/coupling: —— Strong Coupling
····· Weak Coupling

** Symbols: T = Thermal Process
H = Hydrological Process
C = Chemical Process
M = Mechanical Process

TABLE 2.6.2: TREND IN DOSE RELATIONSHIP DUE TO EFFECTS OF COUPLING IN THE GEOSPHERE

Coupling Class	Effect	Dose Trend and Magnitude* (±)
C H	• Fracture filling causing reduced hydraulic conductivity/short-circuiting flow	(?)
	• Dissolution of fracture coating minerals	(?) small
	• Fracture coating/sealing of porous matrix eliminating matrix diffusion	(+) large
	• Colloid formation with nuclides causing enhanced velocity in fractures	(+) large
H M	• Stress-induced fracturing above vault causing increased water flow	(+) small
	• Tectonic fracturing in vicinity of vault providing high permeability pathway to surface	(+) large
T	• Temperature increase/water expansion/ hydrofracturing/thermal convection	(?)
H M		

* (+) indicates increased dose
(-) indicates decreased dose
(?) uncertain effect

2.7 Past Experience with Nuclear Materials

Over the past 50 years, there has been a great deal of collective experience gained in the management of nuclear wastes, and a great deal of insight has been gained through the investigation of natural analogues of conceptual future repositories. It is important that the proponents draw upon this experience and use it in their conceptual design and in the communication of concepts to the Canadian public.

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3.0 WASTE PRODUCTION AND STORAGE

The commercial nuclear industry in Canada currently produces most of its high-level nuclear wastes in the form of spent fuel and is likely to continue to do so into the foreseeable future. There are, however, and will continue to be other types of high-level wastes produced which will require special handling and disposal. These other wastes, because of their physical, chemical and radioactive properties, will require processing and handling procedures that differ from those for spent fuel.

3.1 Materials to be Disposed

In the response to the 11th Hour Report, the government made a commitment to include the question of waste volumes in the public review of the AECL concept. This requires a review of operating and decommissioning wastes, as well as alternative fuel cycles that could reduce both the volume and the risk of wastes produced by nuclear reactors. This should also include an assessment or forecast of energy supply and demand. Alternate fuel cycles could also involve reprocessing to recover plutonium and hence shift the risk to other aspects of the fuel cycle.

The types of wastes to be considered within the environmental assessment should not be limited to used nuclear fuel bundles. This material has relatively uniform characteristics (i.e. shape, radioactivity, weight, etc.) and should therefore be relatively easy to handle. However, large amounts of other nuclear wastes are generated by the nuclear power industry, and these pose unique handling concerns because of their physical, chemical and radiological characteristics.

These wastes include radioactively contaminated materials such as damaged reactor components, pumps, piping, filters, ion exchange resins, etc, all of which are being created in greater volumes with time, and many of which will increase dramatically with decommissioning of reactor facilities. The management of these miscellaneous wastes will require different techniques than those for used fuel wastes, however, all high-level wastes will require proper disposal.

The government also promised, in response to the 11th Hour Report, to assess the disposal of vitrified waste from a reprocessing plant. This assessment should also present the various risks associated with the recovered fission products and outline their

ultimate disposal.

Another element in the discussion of waste types relates to new generations of nuclear power production (e.g. thorium cycle and enriched fuel from slowpoke reactors) and the types and volumes of wastes that could come from such future technology. The inclusion of other types of high-level nuclear wastes may not be compatible with the storage containers proposed by AECL, and this must be considered in the concept review.

The source of the waste (which will in turn be determined by the type of waste being included in the disposal concept) will influence the location of the repository, as well as transportation and other associated factors. The question of whether a Canadian disposal site would be restricted to Canadian wastes or whether it would be used to accept CANDU wastes (or other high-level nuclear wastes) from other countries must be addressed.

3.2 Transport of Alternative Waste Forms

The overall policy developed for the management of other high-level wastes must address both the on-site short- and long-term storage aspects, as well as issues related to reprocessing and concentration, and eventual transportation of the wastes to a permanent repository. Because of the nature of these other wastes, as discussed in Section 3.1, it is likely that cask design may require modification. Such modifications should be included in the overall transportation strategy program. The varying chemical and radiological properties of these wastes must also be taken into account when addressing the transportation risk-related issues.

3.3 Primary Container Integrity

The repository concept, as currently being considered, may be operational for over 50 years. During this period of time, a series of chambers will be excavated, filled with spent fuel, backfilled and sealed. The proposed concept relies on both the fuel bundle matrix itself and the design of the container to prevent radionuclides from being released into the buffer material surrounding the canister. This container needs to be designed and shown to have operational characteristics such that there will be a very high degree of containment for a time period of well beyond the operational life of the repository.

Of crucial importance in this aspect is the integrity of the primary container against leakage associated with abrasions from handling, or corrosion processes that may be expected to occur within the first 100 to 200 years. This will ensure that, if any retrofitting of the disposal vault is required because of knowledge gained over the next century, it can be relatively easily and safely carried out.

4.0 TRANSPORTATION

In order to understand the potential environmental significance of the transportation component of the concept and its interrelationship with other components, it is important that a reference transportation system or systems be developed and presented. The system developed will be dependent upon the particular transportation mode employed (e.g. rail, truck, barge, etc.).

A crucial part of the transportation analysis will be the design of the cask for containing the waste during transport, and possibly during storage at either end of the transportation system. Of considerable interest to the public and national authorities is the issue of safeguards and the manner in which the wastes will be protected during transport against acts of terrorist attack, hijacking or other acts of sabotage.

4.1 Reference Systems

To provide a clear picture of a proposed transportation program, a reference system should be developed. This should include such aspects as follows:

A clearly defined risk and environmental assessment program needs to be included in determining transportation system configuration. Within the base-case system, potential safety, biological, environmental and health risks need to be determined for operations under normal and accident/incident scenarios. Risk parameters must be outlined and performance measures defined. The nature of potential effects (i.e. socio-economic, environmental, cost) must be determined for probable system configurations. Again, this would involve the development of assessment parameters and performance measures. After the completion of these risk and impact identification activities, any compensation and mitigation approaches should be outlined.

At a minimum, a base-case system should include the following components:

A. System Design

1. Assumptions regarding waste form
2. Volumes and timing of used fuel shipments
3. Cask requirements, design and testing

4. Modal (i.e. mode of transportation) mix
5. Routing methodology
6. Shipment monitoring
7. Truck shipment options
8. Rail service options
9. Water service options
10. Vehicle standards
11. Infrastructure needs

B. Operational Procedures

1. Operations plans and staffing
2. AECL/Ontario Hydro carrier requirements
3. Personnel training and experience
4. Cask and vehicle maintenance
5. Vehicle stoppage
6. Notification procedures
7. Vehicle/cargo identification
8. Inspection and enforcement
9. Physical protection
10. Permits and fees

C. Emergency Preparedness

1. Roles and responsibilities of federal, provincial, tribal and local governments
2. Equipment
3. Training
4. Communications
5. AECL/Ontario Hydro response teams
6. Funding

D. Liability and Compensation

1. Federal structure, including precautionary evacuations, emergency response costs and compensation systems
2. Exposure of provincial government(s)
3. Provincial liability limitations

E. Environmental Protection Regulatory Structure

Roles, responsibilities and requirements of federal, provincial, tribal and local governments

F. Comprehensive Risk Assessment and Risk Management System

1. Risk management system scope
2. Risk management system methodologies
3. Risk management system response

G. Transportation System Data Management

1. Potential data needs, including transportation network analysis, highway, rail and water routing; risk assessment and management, shipment monitoring, etc.
2. Determination of conceptual performance standards for the system
3. Alternative methods of achieving performance standards
4. Data sets (available or to be developed) required for studies of environmental and other impacts

A base-case transportation system will provide direction in the development of strategic and short-term planning by clarifying aspects of the program which need to be addressed. It should be noted that not all of the above items are the responsibility of the proponent. For example, Section E is clearly within the jurisdiction of governments.

A strategic plan would demonstrate the sequence and interrelationships of transportation initiatives which would be undertaken in the development of the system. For example, a cask development initiative may be undertaken only after waste forms are identified. Method of transportation may be determined only after transportation facilities for each reactor and type disposal site are surveyed. Routes may be determined only after a methodology for selection is agreed upon. The transportation planning process may also offer opportunities for logical scheduling of public, governmental or contractor participation in the transportation planning process.

4.2 Cask Design

A major question is whether waste forms other than used nuclear fuel, as identified in Section 3.1, may be transported in casks to a disposal site. Plans for cask development or use of present casks need to take into account projected volumes, age and source terms, and thermal characteristics of non-fuel radioactive wastes which may need to be transported. In addition, dual-purpose casks (for temporary storage and transportation) may be feasible within

a transportation system. The use of such casks may be of great value in transportation system and facilities design, storage monitoring, operations or scheduling of shipments. Furthermore, the flexibility provided by the use of such casks would relieve pressure in the event to lack of reactor storage space should the siting, characterization, construction or licensing processes be delayed.

Issues pertaining to transportation/storage cask design which need to be addressed include the following:

1. cask fleet requirements; use of present casks in the used fuel disposal program;
2. analytical methods to be used in cask design;
3. consideration of the principle of As Low as Reasonably Achievable (ALARA) in regulations;
4. adequacy of present cask testing standards (for all waste forms);
5. tracking and monitoring of fuel assemblies and casks;
6. quality assurance procedures for cask design, fabrication and operations;
7. plans for prototype (full-scale) testing;
8. investigations into use of casks for both shipping and storage; and
9. consideration in cask design of modal transfer and emergency response.

A cask tracking and maintenance system is also necessary. Such a system should include the development of cask transponders, the identification of required fixed and mobile cask maintenance plans, identification of cask maintenance requirements, the development of a cask maintenance QA/QC program and the development of a cask maintenance database.

4.3 Safeguards

While the probability of a terrorist attack or an act of sabotage is low, the consequences of such actions may be significant. Not all types of stresses on a cask which may be brought about by acts of sabotage or terrorism are known, and engineers may be unable to design casks to withstand the use of techniques of sabotage and weaponry yet to be developed. Nevertheless, thought needs to be given to such situations which may occur during cask fabrication, handling, transportation and transfer to a disposal site. A first step is the development of a quality assurance program for cask

design, fabrication, testing and operations. Operational scenarios need to be developed and considered, with actual incidents of terrorism or sabotage in mind.

At a minimum, systematic and detailed physical protection planning should include the following:

- scenario assessment
- vulnerability analysis
- screening of management options, including:
  - technical measures
  - organizational measures
  - safeguard measures
  - mitigation measures
  - political measures
- resilience analysis:
  - redundancy
  - diversity
  - mitigation
  - avoidance of regularities
- decision analysis
- sensitivity analysis

Contingency plans for public information, emergency response and enforcement must be developed for those cases which appear most probable. This is a matter of institutional control which must be considered to enhance public confidence in the transportation program.

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5.0 SURFACE FACILITIES

The development of a high-level nuclear waste disposal facility will be, in many ways, very similar to the development of a modern mine in a remote environment. As with any large industrial development, there will be a wide range of environmental effects related to both the radiological and non-radiological aspects of the development. In the short-term under normal operating conditions, it is expected that the non-radiological effects will produce a much broader and more significant range of environmental effects than those associated with radiological effects. It is important that these not be overlooked and that radiological and non-radiological potential effects be balanced in any analysis.

5.1 Surface Facility Development

The permanent repository will have most of the characteristics of a large mining development including all of the support infrastructure, surface facilities such as roads, buildings, waste rock piles, raw materials storage, possibly a small airport, etc. Each of these sub-developments must be addressed in the EIS. In addition, there will be servicing aspects such as water supply, water treatment and disposal, sewage treatment, garbage disposal, air treatment and emissions, etc.

During the past several years, environmental assessments of a number of large mining developments have been carried out. The proponent should consider reviewing these to provide a cross-referencing of specific infrastructure areas to be addressed.

5.2 Interim Regional Storage

In the United States, because on-site storage capacity at some nuclear power reactors is expected to be used up before a national repository is operational, consideration is being given to the design and development of regional interim storage facilities. These areas would provide an interim storage function, as well as possibly allowing for inspection and primary packaging. Depending upon whether the final concept involves long-term waste storage, or possible reprocessing and eventual disposal of Canadian high-level wastes, consideration of regional interim storage sites may be appropriate.

6.0 SUBSURFACE FACILITIES

6.1 Geomechanical Concerns

High rock stresses, greater than those known to exist in other parts of the Canadian Shield (Herget, 1988), have been measured at the Underground Research Laboratory (URL) in the Lac du Bonnett batholith (Martin, 1989). High natural rock stresses have the potential to negatively affect the structural stability and containment properties of the proposed underground vault. This potential may be enhanced by the generation of thermally-induced rock stresses created by heat dissipation from the emplaced high-level radioactive wastes. Consequently, AECL must demonstrate in their EIS, that the occurrence of high rock stresses will not significantly affect overall performance of a nuclear waste repository in plutonic rock in a negative way.

The following sections summarize specific technical subjects associated with this issue. These subjects include available stress measurements, effects on vault stability and containment and thermal effects.

Available Stress Measurements

An extensive program of rock stress measurement has been performed at the URL using a variety of stress measurement techniques. These measurements show the existence of horizontal stresses of up to 100 MPa (Martin, 1989) at depths less than 450 m and horizontal to vertical stresses of up to 10:1 near the surface. High vertical stresses, greater than the calculated lithostatic stress by factors of up to three, have also been measured (Chandler and Martin, 1990), and considerable variation in the orientation of the principal stresses has been observed (Martin, 1989). Many of the measured stresses and stress orientations appear to be related to the occurrence of major fracture zones. Furthermore some of the variability in hydraulic properties of one of the major fracture zones as well as the adjacent rock in the vicinity of the URL is thought to be related to the distribution of in-situ stress and normal fracture stiffness (Martin et al., 1990).

It is useful to compare the data from the URL with other available rock stress measurements. Table 6.1.1 summarizes the available average horizontal rock stress data for the 300 - 400 m depth in Canada and other countries. The average horizontal rock stresses measured at the URL are in general 2.0-2.5 times higher than all of

the other rock stress measurements. The rock stress data for the URL above 250 m are generally consistent with the other shallow stress data referenced in Table 6.1.1.

Because the URL is the only plutonic rock in Canada that has been subjected to extensive stress measurement to depths of 400 m, it is not possible to conclude whether or not the URL rock stresses are anomalous. The frequently cited database of Herget (1986, 1988) as amended by Arjang (1989) is entirely for mining operations located in major structural belts in primarily volcanic and metasedimentary rocks. Ground stresses at these mining locations will likely be less than those of a more massive "high modulus" region such as a sparsely fractured pluton (Fairhurst, 1986).

Effects on Vault Stability and Containment

Excavations completed in highly stressed rock may be a concern for structural stability of the vault depending on the ratio of in-situ stresses to rock strength. At the URL site and therefore possibly at other plutonic sites, the ratio of maximum principal stress (σ_1) to unconfined compressive strength is such that spalling and ground support (e.g., wire mesh and rock bolting) are required below a depth of 250 m. Adjustments of the rock mass to underground excavation also resulted in the formation of extensive microcracks (Martin, 1989), which for the URL shaft were found to be restricted to one shaft diameter beyond the excavation face (Martino et al., 1989), within the time-scale of measurement.

The results of the URL stress measurement program show that significant variation in rock stress can be expected over short distances with geologic structure (fracture zones etc.) and lithology acting as controlling factors. This is consistent with results from many related studies on rock stress (Hyett et al., 1986; Pahl et al., 1986, Arjang, 1989, Brown et al., 1985) and suggests that there will inevitably be significant uncertainty in quantification of rock stresses at repository sites. This general level of scientific uncertainty must be addressed by appropriate engineered safeguards and mitigating actions.

TABLE 6.1.1: SUMMARY OF SELECTED IGNEOUS ROCK STRESS MEASUREMENTS

Location	Rock Type	Average Depth (m)	Horizontal Stress (MPa)	References
URL, Canada	Granite	300-400	40-70	Martin (1989)
Canadian Shield	Volcanics Metasediments Granites	300-400	20-25	Herget (1986)
Gidea, Sweden	Granite	300-500	10-20	Bjarnason et al. (1986)
Forsmark, Sweden	Granite Gneiss Granodiorite Metavolcanics	300-400	20-35	Carlsson and Christiansson (1986)
Cornwall, England	Carnmenellis Granite Batholith	300-400	15-25	Batchelor and Pine (1986)
Canadian Shield	Volcanics Metasediments	300-400	10-20	Arjang (1989)

Excavations completed in highly stressed rocks may result in a reduction in containment in the following ways:

- Stress redistribution resulting in opening of previously closed fractures;
- Formation and slow growth of new fractures and microcracks and development of an annular ring of enhanced permeability;
- Shear slip along pre-existing discontinuities or induced shear failure of enclosing rocks resulting in rupture of an emplaced waste container and release of radionuclides to buffer and backfill material.

Stress redistribution and fracture opening/closure has been observed at the URL (Lang et al., 1987). However permeability decreases due to shaft excavation were observed at some distance from the shaft, whereas 3-D finite element modelling predicted the opposite trend suggesting that the mechanisms involved in the hydraulic response of plutonic rock to excavation are not well understood. Kelsall et al. (1984) and Makurat et al. (1990) show that the actual hydraulic response can be complex depending on site geology, fracture characteristics (orientation, roughness, infilling minerals) and excavation method.

Martin (1989) reports that annular zones of excavation-induced microcracks and extension fractures occurred immediately around the URL shaft at depths of 277 and 300 m. These zones which are reported to extend up to 0.5 m from the face of the opening are likely zones of enhanced hydraulic conductivity as shown in related studies in Sweden (Pusch and Bergstrom, 1988) and in the United States (Montazer and Hustrulid, 1983).

In the event that high shear stresses develop in the rocks surrounding the repository, it may be possible that during either the operating or post-closure phase, shear failure along existing fractures may rupture an emplaced waste container. This rupture would breach the container containment, allowing radionuclides to migrate to the buffer and backfill material.

Thermal Effects

Emplaced high-level radioactive waste in a typical Canadian disposal facility will generate a thermal load in the rock mass which may last for about 10,000 years and result in rock temperature increases of up to 60°C (Wilkins et al., 1985). This thermal load will result in some microcrack formation and the creation of thermal buoyancy to drive groundwater flow through the repository. However, the most potentially significant effect of thermal loading will be the generation of thermally-induced rock stresses as a result of thermal expansion of pore waters and the bulk rocks. Such thermally-induced rock stresses could enhance the potential negative impacts previously described for naturally occurring high in situ stresses (i.e., vault stability and containment).

6.2 Canister Corrosion and Spent Fuel Dissolution

Groundwater Geochemistry

The discovery of widespread saline groundwaters in the rocks of the Canadian Shield was an early and unpleasant surprise in the history of the AECL nuclear fuel waste management program, because of its implications for container corrosion:

> "...it was widely held that [the groundwater chemistry] would be "typical" of Shield terrain; that is, low in total dissolved solids, slightly acidic, relatively high in silica, and in general benign. Early results of sampling across the Shield indicate that this factor may have been badly misjudged." (From the First Annual Report of AECL's Technical Advisory Committee, NFWMP, 1980, TAC-1, p. 37.)

It is now appreciated that recorded occurrences of saline groundwaters in Shield rocks can be traced back to the early reports of the Geological Survey of Canada (GSC) in the 1870s and that modern Canadian hydrogeologists were not aware of similar evidence in more recent reports from the mining industry and the GSC (Frape and Fritz, 1987), or of the significance of the "moose licks" (i.e. saline groundwater discharge of the Nipigon region of northern Ontario).

In virtually all shield rocks highly saline groundwaters have been reported at the proposed repository depth of 0.5-1 km. Within the

Canadian Shield, fresh to brackish waters (0-10,000 mg/L total dissolved solids or TDS) are usually found in the upper 1 km. However, saline waters and brines (>10,000 mg/L TDS) tend to be ubiquitous at depths below 1 km. These waters have a Ca-Na-Cl chemistry with TDS as high as 350 g/L. Representative groundwater chemistry data from AECL research areas on the Shield are presented in Table 6.2.1.

The brines of the Canadian Shield usually occur in large, open fracture zones. The deepest samples obtained from open fracture systems are from boreholes penetrating faults at approximately 2.5 to 3 km below surface. Associated with these brines are considerable quantities of dissolved gases, comprised primarily of methane, nitrogen, argon and locally hydrogen and/or helium (see Table 6.2.2). Methane and hydrogen have been long recognized in the mining industry as major explosive hazards and have been associated with numerous accidents in underground workings.

The occurrence of Ca- or Na-Cl brines and associated methane and nitrogen gases appears to be a very common chemical phenomena in Shield rocks. Comprehensive studies from Finland show that both Ca- and Na-rich brines occur, often within a few meters of the ground surface (Nurmi et al., 1988) Ca- and Na-brines with associated methane-hydrogen-nitrogen gases also occur in a number of Shield environments across Russia (Vovk, 1987). This discovery of saline groundwaters has focused concern on the corrosion of the spent fuel containers and on the dissolution of radionuclides within the spent fuel.

AECL'S Disposal Concept

AECL's nuclear waste disposal concept involves the containment of unprocessed nuclear fuel waste in a plutonic rock repository using engineered barriers to contain the radionuclides for at least 10^4 years with an individual risk of release of 10^{-6} per year. The proposed waste container (2.246 m x 0.633 m) will be fabricated from titanium (or possibly copper) and will have a wall thickness of 6.35 mm. The container will be packed with spent fuel bundles and the remaining volume will be backfilled with glass spheres to provide mechanical support against the lithostatic pressure that is expected to develop after closure. The containers will be

TABLE 6.2.1: CHEMISTRY OF GROUNDWATERS FROM PLUTONIC ROCKS AT FOUR AECL RESEARCH AREAS ON THE CANADIAN SHIELD (All ionic concentrations are in mg/L; blanks indicate no data (from Gascoyne et al., 1987)

Research Area	Borehole	Depth (m)	Na	Ca	Cl	pH	TDS
East Bull Lake	EBL-1	405	242	6	328	10.2	678
	EBL-4	443	846	279	1,743	8.9	3,040
	EBL-2	538	584	293	1,350	7.4	2,282
Chalk River	CR-13	341	209	35	325	7.9	687
	CR-13	576	53	19	29	8.1	282
Atikokan	ATK-1	790	613	978	2,380	6.0	4,114
	ATK-1	880	1,830	11,900	25,400	7.3	40,000
Lac du Bonnet	WN-4	720	3,130	1,860	7,410	-	13,800
	WN-4	800	4,170	1,680	9,570	-	16,760

TABLE 6.2.2: REPRESENTATIVE COMPOSITIONS (in vol. %) OF NATURAL GASES MEASURED IN MINE DISCHARGES AT SUDBURY, ONTARIO (from Fritz *et al.*, 1987)

Sample	N_2	CH_4	He	H_2
N3640A	79.9	9.75	5.3	n/a
N3640B	79.2	8.7	6.8	n/a
N3644B	77.0	14.4	4.7	n/a
N3645	77.2	12.5	6.3	n/a
N3646A	74.6	15.6	6.7	n/a
CCS4000	3.28	55.1	5.17	30.3
STR31178	83.3	0.2	10.2	n/a

contained in cylindrical wells excavated in the floors of the disposal chambers and the volume between the container and the host rock will be backfilled with a mixture of sand and bentonite. Water up-take by the bentonite and the subsequent swelling will ensure a low permeability seal. Finally, as the chambers are loaded with containers, they will be backfilled with crushed granite and glacial lake clay to form a permanent repository.

The "engineered barrier" concept contains a number of mechanical barriers to prevent the untimely release of radionuclides into the surrounding geosphere. First, the waste is encapsulated in the Zircalloy fuel sheathing, which is not in direct contact with a corrosive environment at the time of placement of the container in the repository. Second, the fuel bundles are contained within the sealed titanium alloy container, which in turn is surrounded by a low-permeability bentonite/sand buffer and the rooms backfilled. Finally, the backfill interfaces with a host rock matrix that has been selected to contain a minimum number of fractures and faults.

In addressing the corrosion issues that arise in designing an engineered barrier concept of the type described above, it is necessary to first identify those factors that are likely to have an impact on the rates of degradation of each of the engineered barrier components. Many of these issues have been reviewed in the open literature (e.g., Cameron, 1982; McKay et al., 1982; Nuttall and Urbanic, 1982; Boegly and Alexander, 1984; Day et al., 1985; Marsh and Taylor, 1988) and the problems inherent in predicting container performance are generally well-known. However, this review has identified a number of issues related to corrosion of titanium and copper containers that are specific to the AECL disposal concept and which require additional analysis. The recommendations contained in this review are designed to improve AECL's ability to predict corrosion damage functions for at least 500 years (and hopefully much longer) after closure of the repository and hence to assure the Canadian public that any release of radionuclides to the biosphere will be within the design limits.

Container/Buffer Interface

The first engineered barrier in the disposal concept that is susceptible to corrosion is the titanium alloy/buffer interface. Because of the continual decay of radionuclides in the waste and the conduction of heat into the near-field environment, the temperature at this interface is predicted to exceed 150°C within a few years of closure. Simultaneously, the γ and β dose rates are

predicted to decay with time. Nevertheless, the bentonite/sand/water environment in contact with the container is expected to be subjected to significant radiolysis over an extended period of time (hundreds of years) at elevated temperatures, and the effect of the resulting environment on the corrosion behaviour of the titanium alloy needs to be explored in a more comprehensive manner than has apparently been done to date. This is most important because the container is of a "thin wall" design with little allowance for localized corrosion, such as pitting attack, crevice corrosion, or environment-assisted fracture.

Short term (γ) radiolysis experiments on various proposed construction materials for high-level radioactive waste containers in contact with water or brine have been conducted and the corrosion behaviour of the containers within a period of hours or days of exposure to ionizing radiation is reasonably well understood. For example, these experiments indicate that under the oxidizing conditions that will exist immediately after closure, the corrosion potential is displaced by as much as several hundred millivolts in the positive direction (Glass, 1988) by water radiolysis. On the other hand, similar experiments carried out in simulated and actual boiling water reactor (BWR) core environments under reducing conditions (with excess hydrogen) display the opposite effect; the corrosion potentials of Type 304, 316, and 347 steels are displaced in the negative direction (Andresen, 1990). These reducing conditions might reasonably simulate those that will exist at the container/buffer interface after long exposure times as hydrogen accumulates in the system due to corrosion, or as a result of consumption of oxygen and other oxidizing species (e.g. H_2O_2) by reaction with organic matter or other reductants in the near-field environment. Thus, we expect large changes to occur in the redox state of the container/buffer interface and in the corrosion behaviour of the container. Some of these corrosion issues are explored in more detail later in this review, but it is sufficient to note at this point that pitting attack and crevice corrosion are of concern during the short term under net oxidizing conditions, whereas hydrogen-assisted cracking is of concern at long exposure times under the net reducing conditions that are predicted to exist at the container interface.

Both theory (Macdonald et al., 1981) and experiment (Andresen, 1990) have shown that in radiolyzed aqueous environments corrosion results from strong coupling between the electrochemistry of the substrate metal and the radiolytic products in the solution. Because this coupling is not taken into account or is greatly deemphasized in calculating the redox potential of the environment

(Macdonald et al, 1981), it is not appropriate to use the redox properties of groundwater alone when attempting to predict the occurrence of specific corrosion phenomena. This point is most important because various corrosion phenomena occur at critical corrosion (not redox) potentials that may vary with the thermomechanical and thermochemical states of the substrate and temperature. For example, in the case of the austenitic stainless steels in high temperature water, the critical potential for intergranular stress corrosion cracking (E_{IGSCC}) depends on the degree of sensitization of the steel and on the temperature, but fracture will not occur unless the corrosion potential exceeds E_{IGSCC}. A similar situation exists with pitting attack and crevice corrosion, demonstrating that if one is to explore and predict the occurrence of specific corrosion phenomena it is necessary to predict the variation of the corrosion potential with time. Thus, it is not sufficient to estimate the redox potential or "E_h", in the terminology of geochemists, to address the corrosion issue at the container surface, but knowledge of E_h, itself a mixed potential (Stumm and Morgan, 1981) in most natural waters, is sufficient to determine the thermodynamic stability of non-metallic or non-conducting components in the buffer and near-field environment.

The theory for estimating corrosion potentials for metals and alloys in nuclear waste repositories is now well established (Macdonald and Urquidi-Macdonald, 1990), but because there are significant shortcomings in the database, the calculated corrosion potentials are somewhat unreliable. The mixed potential model used for these calculations demonstrates that the only radiolytic species of importance in setting the corrosion potential are O_2, H_2, and H_2O_2 in addition to H^+ (i.e. pH). However, the same model demonstrates that one also needs to know the polarization characteristics of the substrate alloy. Thus, we recommend that AECL measure current/voltage curves for the designated titanium alloy and the kinetic parameters (exchange current densities, transfer coefficients) for the reduction of oxygen and hydrogen peroxide and the oxidation of hydrogen on the same substrate in simulated near-field environments at temperatures expected at the container/buffer interface. These data, together with transport data for the radiolytic species, should then be used with a suitable mixed potential model incorporating the radiolysis of the fluid in contact with the container to calculate the corrosion potential over the estimated lifetime of the repository. The model should also be used to explore the sensitivity of the corrosion potential to repository and container design parameters and to uncertainties in the various input data, so that the uncertainties

in the corrosion potential over the millennia of waste isolation can be explored.

Prediction of Corrosion Phenomena and Rates

The underlying assumption that only localized corrosion phenomena will be important in the disposal concept appears to be valid because of the high passivity of titanium in aqueous environments. The question of localized corrosion of titanium and titanium alloys in high temperature chloride environments has been addressed by a number of workers (e.g. Posey and Bohlmann (1967) and Koizume and Furuya (1973), and more recently by McKay and Mitton (1935)) who address localized corrosion of titanium and titanium alloys in simulated near-field environments under conditions expected in the Canadian repository. The latter workers dismiss pitting attack as a probable cause of container failure and instead concentrate on crevice corrosion as the most likely form of attack. In our view, recent advances in our understanding of the nucleation and corrosion pits on metals in general suggest the re-examination of this issue in light of the long exposure times involved in nuclear waste isolation.

Prior to about ten years ago, it was believed that metals and alloys would pit in any environment if the corrosion potential exceeded a critical value (V_c). However, experimental work by Shibata and colleagues (1976, 1981, 1983), Williams and coworkers (1983, 1985a,b) and the theoretical work of Macdonald and Urquidi-Macdonald (1981, 1987, 1989) has shown that V_c is a near normally distributed quantity corresponding to a distribution in the properties of the breakdown sites on the surface of the metal. The same experimental and theoretical analyses have demonstrated that the induction time for pit nucleation is also a distributed parameter so that this quantity, cannot be regarded as a unique value either.

Because "pitting potentials" are normally measured using the potentiodynamic technique, in which the potential is swept in the active-to-noble direction at a finite sweep rate (typically 0.1 to 10 mV/s), the measured pitting potential is believed to be too positive because of the time required for nucleation. Accordingly, given sufficient time, metals such as titanium are expected to pit at far less positive potentials such as those available in nuclear waste repositories. We therefore recommend that additional studies be conducted on the pitting behaviour of titanium in simulated repository environments, with the goal of determining "true"

pitting potential using ultralow voltage sweep rate potentiodynamic techniques (10 mV/s to <1 μV/s, followed by extrapolation to zero sweep rate) and potentiostatic tests. The onset of both "unstable" and "stable" pitting should be explored by examining the current noise and mean current, respectively.

The difficulties outlined above in measuring the critical conditions for pitting also apply to the characterization of crevice corrosion. Thus, we also recommend that additional long-term experiments be carried out on creviced titanium specimens to ensure that the conditions under which crevice corrosion can occur are better characterized.

Physico-chemical models have been developed to describe container corrosion in AECL's proposed repository but it is not clear from the information available in the open literature that the models adequately describe the processes involved. Most models developed for evaluating the impact of corrosion on containers over millennia of time are too simplistic, in that they do not adequately couple all of the transport and thermal phenomena that occur in the system. For example, it is essential to couple the thermal properties with radiolytic and mass transport processes to adequately describe the availability of oxidizing species (O_2, H_2O, H_2O_2, H^+) at the container surface. The reason for this is that temperature gradients and water radiolysis place the oxidizing species much closer to the container surface than otherwise would be the case. Indeed, by coupling the phenomena identified above with the anodic and cathodic reactions that occur at the container surface, it is feasible to describe the corrosion properties of the container over the lifetime of the repository as the temperature and dose rate decay with time.

One particularly interesting potential scenario is that the rate of corrosion will be limited by the transport of oxidizing species to the container surface. Indeed, this represents the maximum rate at which corrosion can occur so that it may prove useful in determining the upper limit for the rate of container degradation as the repository evolves with time. Accordingly, we recommend that more comprehensive models than those currently available be developed to explore the evolution of the corrosion properties of the container with time. These models should also be used to explore the sensitivity of the corrosion damage function with time over the design life of the repository and with uncertainties in the input data and model parameters. In light of the above, the corrosion behaviour of the container in the near-field environment should be re-examined with particular emphasis on the long-term

evolution of the damage functions (pit depth vs time and crevice attack rate vs time).

In the event that the container is breached by corrosion, the remaining engineered barrier between the environment and the fuel is the Zircalloy fuel sheath. Accordingly, it will be necessary to use the models outlined above to estimate the susceptibility of Zircalloy to corrosion, with appropriate adjustments being made for differences in dose rate and temperature. Finally, any breachment of the Zircalloy will expose the spent fuel (predominantly UO_2) to the environment so that consideration must be given to dissolution of this substrate as well. In the highly defective state, the fuel is expected to have good electronic conductivity, so that dissolution may be described as an electrochemical phenomenon; the rate of which would depend on the redox conditions in the system. Assuming that appropriate experimental data are measured for key kinetic parameters, it should be possible to predict the release rate on the basis of the mixed potential model described above.

Microbially-Influenced Corrosion of Containers and Fuel Elements

In recent years, there has been better appreciation of the role of microbes in the corrosion of metals in groundwater systems. The possibility of microbially-influenced corrosion (MIC) in nuclear waste repositories has been extensively reviewed by West and others (1982, 1985) and it was concluded that microbial attack poses a significant threat to container integrity. Most of the work carried out on MIC in nuclear waste repositories has been concerned with iron and iron-based alloys and not much is apparently known about microbially-induced corrosion of titanium alloys, although titanium is generally thought to be immune to microbial attack. Of particular importance is the ability of microbes to affect the local redox and corrosion environment (i.e. by microbial catalysis of thermodynamically favourable relations), perhaps by displacing the corrosion potential of the subtended alloy to the extent that pitting corrosion becomes possible. We therefore recommend that a thorough review be carried out of the possibility of MIC on titanium.

Corrosion is greatly intensified in systems where a consortium of microorganisms with widely different physiological propensities can concentrate their metabolic versatility into relatively small areas of intense activity. Corrosion is essentially an electrochemical activity wherein metal is lost by an anodic (oxidation) reaction with the production of electrons that are distributed to cathodic

sites where surface (reduction) reactions such as hydrogen formation or oxygen reduction to water are stimulated. Bacteria facilitate both the anodic and cathodic reactions by a series of mechanisms (White et al., 1985, 1986, 1988 and 1990a).

Microbially-influenced corrosion can be assessed in an on-line manner using non-perturbation or perturbation-response techniques which are non-destructive to the microbial biofilm on the metal surface (Dowling et al., 1988, 1989). Flow-through continuous-culture test systems in which specific metallic surface treatments on material compositions can be tested against consortia of bacteria isolated from corrosion tubercles in diluted growth medium have been utilized to define conditions by which MIC is stimulated or repressed (Franklin et al., 1988). In this system it was possible to show that certain combinations of bacteria that form in specific proportions in a biofilm generate higher average corrosion rates and have a greater propensity to form localized (pitting) corrosion than others even though other combinations of bacteria may exist in higher concentrations (Jack and White, 1990 and White et al., 1990b).

It was also shown that combinations of both aerobic and anaerobic bacteria in biofilms generated in aerobic systems, particularly where the sulphate-reducing bacteria were involved and the sulphate ion in the bulk fluid was at significant concentrations, produced significantly greater MIC (Dowling et al., 1987a). The corrosion induced by mixed microbial consortia containing sulphate-reducing bacteria was active in systems containing less than 0.5 mM sulphate indicating that traces of sulfate can be recycled to produce intensive pitting corrosion in highly localized areas (Jack and White, 1990; White et al., 1990b). In these systems it was possible to utilize a number of on-line non-destructive methods to detect the formation of biofilms of bacteria (White et al., 1990c) and to show that MIC activity correlated with the metabolic activity of the biofilm microbial consortia (White et al., 1990b; 1990c).

The microbial consortia that are involved in MIC are attached to the metal surfaces. Studies have shown that microbes attaching to surfaces in flow gradients are able to markedly change the composition and activity of their surface components when attachment occurs in a shear gradient (Mittelman et al., 1990); a clear demonstration of their metabolic versatility. Changing the charge on the metal substratum markedly effects the composition of the microbial consortia that attach and stimulates some specific metabolic activities (Guezennec et al., 1988). Increasing the

negativity by cathodic poising of a surface component greatly stimulated the hydrogen utilizing sulphate-reducing bacteria so much so that when the uniformity of the charge field was disturbed by various activities the localized MIC increased remarkably and the metal failed rapidly. Microbes may stimulate the localized corrosion of metal substrata by either facilitating anodic reactions (such as promoting metal oxidation and solution), stimulating the utilization of electrons with reductions at cathodic sites, or both.

A hallmark of MIC is its localized activity particularly at sites of increased "energy" at the metal surface (Dowling et al., 1987). The localization can now be mapped non-destructively with the scanning vibrating electrode technology (SVET) where the charge density can be mapped over a surface (Franklin et al., 1990a; 1990b). Understanding of this localized activity of microbial consortia is particularly important for the containment of high-level radioactive wastes over long periods of time.

The second feature of microbial activity that is important in the breaching of containment is the capability of microbes to mobilize radioactive waste elements. One of the most effective ways to mine uranium is to utilize acetogenic bacteria that are autotrophic and capable of greatly increasing the solubility of uranium by oxidizing it to the hexavalent ion (McCready and Gold, 1990). Autotrophic bacteria generate all their nutrient needs from inorganic metals and salts with carbon dioxide as their carbon source. A typical autotrophic organism is *Thiobacillus ferroxidans* which can generate energy by the oxidation of reduced sulphur (usually sulphide) or ferrous iron in the presence of oxygen. This organism is ubiquitous and responsible for acid mine drainage.

The walls of microbes and their extracellular polymer secretions contain complex polysaccharides with both amino and carboxyl moieties on the major charged groups. There are more negatively charged groups on the microbial surfaces, so cations like metals are more likely to be bound than anions (McLean and Beveridge, 1990). Wall envelopes, purified peptidoglycan and the exopolymers have been shown to bind a multitude of metal ions. The exopolymers of bacteria contain uronic acids and amino uronic acids with a large excess of carboxyl groups. The polymers themselves in the absence of the host bacteria or any bacterial activity, have been shown to be capable of facilitating corrosion (Geesey and Jang, 1990; Nivens et al., 1986). One of the methods by which bacterial consortia facilitate corrosion is the chelation of dissolved free metals released at anodic sites. This continuous

process effectively decreases the concentration of free metal ions and catalyzes the solution equilibrium process in favour of enhanced corrosion.

Input Data

When modelling the redox behaviour of the environment and the corrosion behaviour of the containers, it will be necessary to derive numerical values for the various input parameters. Many parameters, such as species diffusivities and the transport properties of the solution (thermal conductivity, viscosity, etc.), probably can be estimated with sufficient accuracy for most modelling purposes. However, other parameters cannot be estimated and hence should be determined experimentally. For example, no experimental data are currently available for the kinetic parameters (exchange current densities, transfer coefficients) for the reduction of oxygen and hydrogen peroxide and the oxidation of hydrogen on the fuel sheathing and container materials of interest (Zircalloy, titanium, copper). Nor are there reliable current voltage curves (potentiostatic as opposed to potentiodynamic) for substrates. These data are required to model container degradation phenomena and must be obtained experimentally because no adequate theory exists for their estimation. Similar data are required for describing the dissolution of UO_2 in the event of a breachment of the Zircalloy fuel cladding.

Fuel Dissolution

Breaching of the waste container and the Zircalloy sheath will expose spent fuel to dissolution and leaching, making the radionuclides available for transport in the fluid or gaseous phase. The rate of radionuclide release will depend on the chemical form of the spent fuel elements and the prevailing geochemical environment. Potentially volatile radionuclides will be available for transport within tens of years of breaching, given that appropriate transport gradients exist. The transport availability of more stable compounds will be dependent on the waste form, its solubility in the transport medium, and the kinetics of the dissolution reactions. Dissolution and transport of the exposed waste will also be affected by the local geochemistry, including changes in fluid and rock temperature, fluid and rock pressure, and changes in the rate of fluid flow.

The spent fuel bundles will probably contain some combination of soluble to relatively insoluble non-volatile compounds and volatile compounds. The release of radionuclides and other ionic species from the spent fuel bundles will depend on the actual solubilities of individual compounds and their solubilities relative to the bulk waste form.

According to Kerrisk (1984), the various classes of compounds in a spent nuclear fuel waste form will behave in the following manner relative to one another. Relatively insoluble, non-volatile compounds such as those containing americium and plutonium will dissolve slowly and will be released to the dissolution medium at a slower rate than the entire waste form. Compounds containing carbon, technetium and neptunium are slightly more soluble than the relatively insoluble compounds, and will probably release radionuclides at the same dissolution rate as the bulk waste form. Volatile and soluble radionuclides such as cesium and iodine will probably be concentrated at the surfaces of the spent fuel elements and will be volatized, dissolved and released to the dissolution medium more rapidly than the majority of the bulk waste form. As with any geochemically controlled dissolution phenomenon, the dissolution rates will be a function of kinetic factors determined by the local geochemical environment and the compounds themselves.

CANDU spent fuel is dominantly uranium-oxide (UO_2), a stable compound in reducing environments. In oxidizing environments, U^{+4} will be oxidized to U^{+6} according to the reaction:

$$UO_2 + 1/2\ O_2 + 2H^+ \rightarrow UO_2^{+2} + H_2O$$

UO_2 is available to combine with available oxygen to produce other uranium-bearing oxides. Because U^{+6} oxides are orders-of-magnitude more soluble than U^{+4} compounds, the formation of U^{+6}-bearing compounds will contribute to disaggregation of the spent fuel and make more U^{+6} available for dissolution and release to the dissolution medium.

The EIS should evaluate the potential oxidation-reduction conditions expected to be present when the waste container and the Zircalloy sheath are breached. The evaluation, preferably in the form of a geochemical model, should simulate the dissolution potential of the spent-fuel waste form under a variety of oxidation-reduction environments that cover the range of expected geochemical conditions at the time of breaching. In addition, where output from the geochemical model of spent-fuel dissolution indicates release of radionuclides to the dissolution medium, the

retardation capability of the buffer and backfill materials with respect to the released radionuclides must be evaluated in the flow and transport model.

6.3 Effect of Temperature and Salinity on Buffer Materials

The AECL concept calls for the emplacement of the spent fuel waste containers in holes in the floor of excavated rooms within the vault. The containers are then to be surrounded by a buffer material that will fill the hole, the rooms will be backfilled and the tunnels and shafts sealed. The purpose of the buffer is prevent the access of groundwaters to the containers and to minimize the flux of radionuclides that might escape from the containers into the geosphere. The purpose of the backfill is to "minimize the flow (of groundwater) in the excavated openings of the rock" (Johnson et al., 1987), although the seals should also play this role.

Therefore, the buffer materials play an essential role in the multibarrier concept advanced by AECL in that they minimize the migration of radionuclides which have leached from the containers into the geosphere. Any radionuclides which escape the buffer will enter the biosphere unless retained in the geosphere. Because AECL has yet to prove in field tracer tests that plutonic rocks can act as a barrier (see 7.3), and because of the likely corrosion of significant numbers of containers within 2,000 years, the functioning of the buffer materials is critical to the overall safety of the concept.

AECL has made the assumption that all the containers will corrode within 500 years and will result in the instantaneous release of significant amounts of ^{129}I, ^{135}Cs, ^{99}Tc, ^{79}Se, ^{126}Sn, ^{3}H, ^{14}C and ^{90}Sr. Thus it is imperative that AECL demonstrate that the reference buffer material, an equal mixture of silica sand and Na-bentonite, be capable of retaining the escaped radionuclides at elevated temperatures and salinities. This is of increased importance following the report by Couture (1985) that steam will cause a reduction in the swelling capacity and an increase in the hydraulic conductivity of bentonite-sand mixtures.

Three issues are of particular importance:

1. the effect of elevated temperatures on the sorption of the above radionuclides by the reference buffer material;

2. the effect of elevated salinities on sorption; and
3. the choice of buffer materials to selectively sorb critical radionuclides.

Effect of Temperature on Radionuclide Sorption

There are three possible implications for an increase in temperature on radionuclide sorption:

a) the effect on the point of zero charge;
b) the effect on adsorption; and
c) the effect on ion-exchange equilibria.

As a first approximation, the temperature dependence of the point of zero charge (pzc) (i.e. the solution pH at which the net surface charge of a sorbent is zero) is due to the increased ionization of water with temperature. Tewari and McLean (1972) and Tewari and Campbell (1976) showed that the changes in the pzcs of Al_2O_3, Co_3O_4, and NiO are completely accounted for by the change in the ionization constant of water, while the proportionately greater change in pzc for the other minerals is due to lattice defects (Fe_3O_4) or disordered structures or aging processes ($Co(OH)_2$ and $Ni(OH)_2$). Machesky (1990) has summarized this data and that of others and shown that proton adsorption enthalpies of most oxides are exothermic (i.e. proton adsorption is not favoured by an increase in temperature).

Anionic adsorption enthalpies for representative anions such as iodate and fluoride on the iron oxide goethite are also exothermic at surface coverages <80% of maximum (Machesky, 1990). Thus, the sorption of the critical anionic radionuclides ^{129}I and ^{99}Tc do not appear to be favoured by an increase in temperature caused by the heating of the buffer materials by the spent fuel containers. However, the existing data (e.g. Tewari et al., 1972; Machesky, 1990) suggest that metal cation adsorption on metal oxides is endothermic and therefore is favoured by an increase in the ambient temperature of the buffer. As Machesky (1990) observed, "it is far from certain that all adsorbed cations and anions will follow [these trends]".

A much greater database exists for ion-exchange equilibria involving alkali and alkaline earth cations and clay mineral exchangers (see Bruggenwert and Kampworst, 1979). For experiments involving monovalent-monovalent exchange, the reaction is generally

exothermic ($\Delta H_{ex}<0$). However, for reactions involving divalent-divalent exchange and monovalent-divalent exchange $\Delta H_{ex}>0$ and the reactions are endothermic. As Helferrich (1962) has pointed out, ion-exchange selectivity often decreases with temperature because the association processes that favour selectivity are discouraged by an increase in temperature.

Therefore, there is a need for AECL to document the effect of temperature on the sorption of critical radionuclides onto buffer materials. Particular concern should be paid to anionic radionuclides such as ^{129}I and ^{99}Tc.

Effect of Salinity on Sorption

The effect of saline groundwaters on the sorption of radionuclides by buffer and other earth materials has long been a subject of interest to geochemists. Wahlberg and colleagues (1962, 1965) showed that Cs(I) and Sr(II) sorption on clay minerals varied inversely with salinity. Rafferty et al. (1981) showed that in 0.1M NaCl groundwaters (e.g. those at the URL) the ^{90}Sr partition coefficient would be approximately 100 L/kg, suggesting a retardation factor of several hundred. Meyer et al. (1984) showed that although the sorption of transition metals such as Eu(III) on hydrous metal oxides appeared unaffected by increasing salinity, Tc(VII) sorption decreased significantly. Thus, the various coupled effects of elevated temperatures and salinity on radionuclide sorption on the reference buffer materials require careful examination by AECL.

Choice of Buffer Materials for Selective Sorption

Because of the crucial role that the buffer plays in retaining radionuclides released from the containers, there have been various suggestions made to include specific solids in the buffer to act as scavengers or selective sorbents for critical radionuclides. For example, Krauskopf (1988) has suggested adding ferrous phosphate to bentonite "to keep infiltrating groundwater both alkaline and reducing, properties that would slow the rate of corrosive attack on canister metal and could immobilize some escaping radionuclides as insoluble precipitates." Presentations made to Environment Canada by AECL at the Whiteshell Nuclear Research Establishment in June 1990 did not suggest that such work was being considered by AECL.

A particular concern exists with the retention of ^{99}Tc, which is both anionic and long-lived, and therefore is considered to be a critical radionuclide in performance analyses of high-level radioactive waste disposal. Should the geochemical environment within the buffer after closure be somewhat oxidizing due to radiolysis, then it has been suggested that magnetite might be an effective scavenger for Tc(VII) (Bondietti and Francis, 1979). Alternatively, if reducing conditions prevail within the buffer, work by Walton et al. (1986) suggests that seeding the buffer with Fe(III) oxyhydroxides should cause the retention of Tc(IV) by chemisorption reactions. Therefore, the use of hydrous metal oxides and zeolites as scavengers appears to offer the possibility of increasing the retention capacity of the buffer materials even in the presence of elevated temperatures and ionic strengths.

6.5 Potential for Gas Generation Accumulation and Migration

Sources and Origins of Gases

The occurrence of gases in the vaults of nuclear waste repositories and the potential for the migration of the gas phases through the geosphere is a matter of considerable concern in the U.S., German and Swedish high-level nuclear waste programs. There are five potential origins or sources of gases that might accumulate or be generated within the vault and which should be accounted for by AECL in the computation of a gas budget for the repository:

1. gases trapped within the vault that were part of the room air;
2. gases dissolved in or associated with the groundwaters of the Shield;
3. gases produced through the microbial degradation of organic materials;
4. gases produced by radiolysis of the groundwater;
5. gases due to corrosion of the containers; and
6. gases produced by radioactive decay of the nuclear waste.

The first two sources and the last are perhaps the easiest to quantify. The room air should contain approximately 78% nitrogen (N_2) and about 20% oxygen (O_2), although the exact amount will depend upon the amount of O_2 consumed by respiration and vehicular combustion during fuel disposal and room closure operations. Some of these gases, most importantly O_2, will no doubt be trapped

within the buffer materials surrounding the canisters containing the spent fuel and in the backfill. The gaseous composition of groundwaters on the Canadian Shield has been documented by Fritz et al. (1987) and shown to be dominated by N_2 and methane (CH_4), with lesser amounts of helium (He) and hydrogen (H_2). These measurements have provided only relative concentrations of gas exsolved from unknown volumes of water; absolute concentrations have yet to be measured. Experiments to be conducted at the URL to simulate vault closure and geochemical testing of the groundwaters surrounding the host rock chosen for the Canadian repository will provide better estimates of both of these gas sources.

Other gas sources are much more difficult to quantify and require making a series of assumptions about the vault environment over the first 10,000 years of disposal. During the operational phase of the repository a variety of microbially-degradable materials will be deposited in the vault. These include diesel exhaust fumes and lubricants from the vehicles used to transport the containers within the vault and oxidizable organic matter within the lake clays comprising the backfill and within the bentonite comprising the buffer materials. Following closure, dissolved organic carbon (DOC) will be introduced by the groundwaters that invade the vault. These are expected to contain perhaps no more than 1 mg DOC/L, but the value has not yet been measured. Microbial activity, either aerobic or anaerobic, halophilic or nonhalophilic, will likely consume all or some of these substrates and produce carbon dioxide (CO_2) and other gases that may include CH_4, N_2, and hydrogen sulphide (H_2S) providing the pH and oxidation-reduction conditions are favourable.

Radiolysis of groundwater will cause the dissociation of water in the vicinity of the containers, producing O_2 and H_2. Because H_2 diffuses more rapidly than O_2 and therefore may migrate away from the container/buffer interface, an oxidizing environment may be left near the containers (Krauskopf, 1988). This process is of great importance in the assessment of the corrosion potential of the containers.

Another source of gas production is the corrosion reaction itself. H_2 can be produced by the gamma radiolysis of water and by the anoxic corrosion of titanium (Johnson et al., 1987). In the process, O_2 will be consumed. Once corrosion has compromised the integrity of the container, gaseous radionuclides will diffuse into the backfill. These will include ^{85}Kr, ^{133}Xe, ^{14}C and ^{3}H, for which estimates of the rate of production should be readily available from experimentation.

These six sources, and possibly other sources of gas production or accumulation, suggest that it would be appropriate for AECL to develop a gas budget for the repository that would allow the estimation of the relative importance of these sources. Such a budget is being calculated for the Waste Isolation Pilot Plant (WIPP) in New Mexico by Sandia National Labs (1989).

Gas Migration

A particularly important concern that appears not to have been addressed by AECL is the potential for the migration of a gas phase from the vault into the geosphere and, conceivably, the biosphere. Performance analyses of gas migration have been undertaken for the WIPP site in New Mexico (Davies et al., 1990), the Konrad mine in Germany (Intera, 1989), a low- and medium- level waste (L/MLW) repository, and the Forsmark L/MLW repository in the seabed immediately adjacent to Sweden (Intera, 1986).

The gas migration models in the above examples account for both the gas dissolved in the groundwater and that in a free-gas phase. These are simulated as two immiscible fluids being transported through a dual porosity geological medium (i.e. the primary porosity of the rock and the secondary porosity of the fractures). Darcy's law is applied to both groundwater and gas flow to produce a momentum equation. The density and viscosity of the fluids are assumed to be a function of the fluid pressure only.

These models indicate that gas release from the repository into the host rock is dependent upon the permeability of the host rock, the gas-water capillary pressure difference between the host rock and the repository, and the gas generation rate. Gas migration occurs in four steps: (1) gas dissolution in water; (2) build up of gas saturation to the critical gas saturation; (3) pressure build-up in the repository; and (4) gas migration into the host rock.

Gas migration obviously affects groundwater flow. Simulations suggest that gas release will typically occur at the downstream end of the repository (with respect to groundwater flow), and that the gas will immediately rise to the bottom of the nearest overlying impermeable rock where gas saturation can develop and produce a gas bubble. The development of a gas bubble causes the deflection of groundwater flow around or through the repository. While the gas bubble is building, dissolved gas continually migrates away from the vault.

There is a clear need for such gas-phase simulation modelling to be undertaken by AECL for the repository environment. This modelling should include thermal effects and make allowance for a zone of increased permeability around the vault due to stress release mechanisms.

Section 6 References

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7.0 GEOSPHERE

The following sections document the basis for the initial choice of plutonic rocks as the disposal medium by highlighting recent developments in our understanding of the hydrogeology, geomechanics and geochemistry of plutons, and by describing some of the available results from research programs considering alternative disposal media.

In 1974, AECL requested the Department of Energy, Mines and Resources (EMR) and the Geological Survey of Canada (GSC) to review proposed disposal technologies in geologic formations and recommend which formations might be suitable for Canada. The review indicated hard rock formations (particularly plutons) within the Precambrian Shield and to a lesser extent salt formations might be most appropriate (Scott and Charlwood, 1980).

In 1975, AECL and EMR established a scientific research program to determine the feasibility and safety of geological disposal of radioactive waste in plutonic rocks and salt deposits (Gale et al., 1981). By 1977 minor consideration was also given to ultra-mafic rocks such as serpentinite, but plutonic rocks were the preferred disposal media because they were considered to be "of suitable size for a repository, ... relatively homogeneous,...structurally competent,... lacking mineralization, ... of low seismicity, and having central location in Canada" (Tammemagi et al., 1977). Hydrogeologic considerations were implicitly assumed to be favourable in plutonic rocks, "because at the depths considered water movement is expected to be very slow indeed" (Boulton, 1978). The decision to chose plutonic rocks was rendered despite the fact that virtually no information on groundwater flow in igneous terrain was available at the time (Tammemagi et al., 1977).

Although the decision to prioritize plutonic rocks for disposal research was established by 1976, the Hare Report (Aiken et al., 1977) is the most frequently cited reference for justifying the selection of plutons as the preferred disposal medium. The Hare Report was commissioned to review disposal alternatives for Canada based on available national and international experience. It was completed in August 1977 after six months of enquiry. It recommended deep geologic disposal in plutonic rocks with salt as a second choice and shaley rocks as the third choice. The Hare Report also noted that deep ocean burial might be suitable. The rationale for selection of plutonic rocks as given in the Hare Report is worth repeating here (Aiken et al., 1977, p. 46):

> "on the balance, we are inclined to believe that the best potential is in plutons, 5 km in diameter and which are, as far as can be determined from present data, not intersected by faults (loci of earthquakes), that are substantially homogeneous, that have no obvious linearity or fractures and which are "dry" or as nearly so as is likely to be achieved".

This recommendation was made prior to any significant hydrogeologic investigation of igneous or plutonic rocks for disposal purposes in Canada or elsewhere in the world. At the time, only limited information was available in Canada concerning the hydrogeology of igneous rocks at depth. This information was mostly derived from inspections of operating mines (Raven and Gale, 1985) which were often located in major structural zones and might not be representative of plutons. Deep drilling and testing at AECL research areas commenced in July, 1977 at Chalk River in a granite gneiss (Raven, 1980) and therefore these early data were unavailable at the time of the report. Consequently, the decision to pursue plutonic rocks was taken before any significant research into the hydrogeology of plutonic rocks at the reference depths of 500 to 1,000 m.

Results of Post 1977 Research on Igneous Rocks

Virtually all of the current hydrogeologic, geochemical and geomechanical knowledge on plutonic or igneous rocks at the reference disposal depths became available after 1977. The Swedish investigative program of field sites and the Stripa underground mine began in April 1977 following passage of government legislation requiring demonstration of safe final storage of spent nuclear fuel (SKBF/KBS, 1983). Similar research programs studying igneous rocks in France, United Kingdom, United States, Switzerland and Finland commenced after 1977. Table 7.0.1 summarizes the current preferred disposal media for high-level radioactive wastes by different countries.

TABLE 7.0.1: SUMMARY OF PREFERRED DISPOSAL MEDIA FOR HIGH-LEVEL RADIOACTIVE WASTE*

Country	Geologic Medium	Reference Depth (m)
Belgium	Clay	220+
Canada	Plutons	500-1,000
Germany	Salt dome	840
Finland	Granite	500
France	Granite, schist, clay or salt	-
Italy	Clay	-
Japan	Crystalline rocks or sedimentary rocks	Few hundred
Netherlands	Salt domes	-
Spain	Crystalline rocks, salt or clay	-
Sweden	Granite	500
Switzerland	Granite and/or sedimentary rock	1,200
United States	Tuff and salt	300 and 650
U.S.S.R.	Salt	-

* From Lieb (1988) and Acres International Ltd. (1989).

Since 1977, the following significant discoveries have improved our knowledge of the hydrogeologic, geochemical and geomechanical characteristics of igneous rocks in Canada:

- the occurrence of saline waters and brines throughout the Canadian Shield below depths of about 500 m was documented;
- the occurrence of extensive high permeability fracture zones and faults that control the development of regional groundwater flow systems were discovered and reported; and
- the occurrence of high ground (i.e. rock) stresses were measured at the anticipated repository depths.

The presence of deep brines with Ca-Na-Cl chemistry and total dissolved (TDS) solids of up to 350 g/L was unforeseen in the AECL program. Such high salinities and TDS have significant implications for container corrosion as well as radionuclide migration in the geosphere (see Section 6.2). The occurrence of brines with high TDS and therefore increased fluid density also has implications with respect to assessments of groundwater flow. Variable density formation-fluids introduce significant complexities into assessments of regional groundwater flows (Hubbert, 1940; Oberlander, 1989; Senger and Fogg, 1990).

The occurrence of extensive high-permeability fracture zones and faults was also largely unforeseen. Investigations performed at the Underground Research Laboratory (URL) near Pinawa, Manitoba identified major subhorizontal fracture zones. Similar permeable fracture zones with various orientations were identified at Chalk River (Raven, 1986), Whiteshell (Davison, 1981), Atikokan (Pearson et al., 1984) and East Bull Lake (Raven et al., 1987). The importance of these fracture zones to the development of groundwater flow systems in igneous rocks is now recognized, and a number of international disposal programs have incorporated discrete high permeability fracture zones in performance assessment modelling of waste repositories (McCombie et al., 1989; Neretnieks, 1989).

High rock stresses, greater than those known to exist in other parts of the Canadian Shield (Herget, 1988), have been measured at the URL in the Lac du Bonnett Batholith (Martin, 1989), where horizontal stresses of up to 100 MPa were measured at depths less than 450 m and horizontal to vertical stresses of up to 10:1 were determined. As the URL is the only AECL research site to have had extensive stress measurements, these stresses may or may not be

representative of in-situ stresses in other plutonic rocks. High rock stresses have potentially negative impacts on repository stability and containment. The high rock stresses may induce rock stability concerns (spalling, rock bursts) during construction and operation of a disposal facility and later after closure when additional stresses due to thermal loads are created. Such stability concerns may also result in failure of an emplaced waste container and release of radionuclides to the buffer or backfill material. High rock stresses may also directly affect containment properties of the vault through the formation of zones of enhanced permeability adjacent to the mined openings by microfissure formation and shear dilation of existing fractures. This new information on high rock stress may require modifications to various aspects of the conceptual design (e.g. container spacing, repository depth, design of engineered safeguards, etc.).

Alternative Disposal Media

Alternative disposal media suitable for Canadian consideration include salt, shaley rocks and the deep seabed (Aiken et al., 1977). Salt was initially studied by AECL through literature studies performed by the GSC. AECL has not performed field studies of bedded salt deposits but monitors progress made through other international research programs investigating bedded salt (see Table 7.0.1).

Shaley rocks were recommended in the Hare Report as a alternative disposal medium because of their presence in Ontario, their relative impermeability and their excellent sorption characteristics. Although AECL has not directly studied shaley rocks, Ontario Hydro has maintained a minor research program to evaluate the merits of disposal in or beneath a blanket of sedimentary rocks (Heystee and Freire-Canosa, 1988). This program has included field investigations of the sedimentary sequences at selected locations in Ontario. Several researchers have indicated that such disposal in a mixed geologic environment would enhance the safety of a deep geologic disposal facility (Russell and Gale, 1981; Fyfe et al., 1984). Shaley rocks may have an added attribute in that a thick shale sequence is located in southern Ontario, in close proximity to the centres of nuclear power production.

The experience of the Swiss high-level radioactive waste disposal program is of particular interest to Canada in that the Swiss program also selected crystalline rocks as the preferred disposal medium in the late 1970s. Based on field investigations performed

in the early 1980s and a government review of the proposed disposal concept in 1988, the Swiss program is now considering both crystalline and sedimentary rocks.

The Technical Advisory Committee on Nuclear Fuel Waste Management Program (Shemilt et al., 1989) has suggested that AECL evaluate crystalline rocks other than plutons such as gneisses, principally because of the high rock stresses measured at the URL. Less isotropic rocks such as gneisses might possess more favourable geomechanical properties than the massive granitoid rocks at the URL.

Deep seabed disposal was identified in the Hare Report as a disposal option that Canada should monitor, and in which it should initiate some research. Canada has participated in international research in this area conducted under the auspices of OECD/NEA Seabed Working Group on Disposal (Whitaker, 1987). Recent radiologic assessments of the consequences of disposal in seabed sediments in deep oceans has been performed within this Group. These studies (de Marsilly et al., 1989) show that seabed disposal appears to be a possible option.

7.1 & 7.2 Major Fracture Zones and Groundwater Flow

Groundwater flow and solute transport in plutonic and other igneous rocks occurs primarily along structural discontinuities such as joints and fracture zones. There is overwhelming evidence from all site investigations performed within Canada and other nations in support of geologic disposal of radioactive waste in crystalline rocks, that the most probable pathway for migration of radionuclides from the disposal vault to the biosphere will be via groundwater flow in discrete relatively high permeability fracture zones. Consequently a demonstrated ability to identify and characterize major fracture zones is crucial to credible assessment of potential repository sites and ultimate selection of a site. AECL, therefore, must demonstrate in their EIS that they can reliably determine the size, orientation and hydrogeologic, geochemical and geomechanical properties of major fractures and other permeable structural discontinuities over the large spatial scales involved in deep geologic disposal.

Hydrogeology of Plutonic Rocks

The study of the hydrogeology of plutonic rocks at the reference depths envisaged in geologic waste disposal is a recent endeavour. Before consideration of waste disposal, there was little motivation to study groundwater flow and solute transport in plutonic rocks. Consequently, virtually all of our knowledge regarding the hydrogeology of deep (>100 m) plutonic rocks has evolved within the last 20 years.

Despite this compressed time frame, we have determined, largely from empirical studies, some fundamental characteristics of groundwater flow and solute transport in fractured crystalline rocks such as plutons. These characteristics are described below as an introduction to subsequent sections which address the issue of identification and characterization of major fracture zones.

Fluid flow and solute transport in any geologic medium requires an interconnected pore space. In plutonic rocks, structural discontinuities, ranging from microscopic (micro-fissures, grain boundary cracks) through macroscopic (1-100 m length systematic joint sets) to megascopic (km length regional fracture zones and faults), provide this void space for fluid flow and solute transport. Our present understanding of fluid flow and solute transport in plutonic rock is limited to studies of these processes in single fractures and simple idealized multiple fracture systems.

Within a single fracture, permeability results from the interconnection of voids, or openings, created by load-carrying asperities that bridge the fracture open. The complex distribution of openings within a fracture plane can result in tortuous flow pathways and independent flow channels. Direct measurement of fracture openings in laboratory experiments (Witherspoon and Long, 1987; Gale, 1987) and comparison of hydraulic and tracer test results in single fractures (Novakowski, 1988; Silliman and Duell, 1988), indicates that idealized flow through smooth parallel plates is inappropriate for natural fractures. Many researchers maintain that fluid flow in fractures occurs principally in high-permeability channels (Neretnieks et al., 1990, Tsang and Tsang, 1987) and there is some direct field evidence to support this belief (Abelin et al., 1990).

Fluid and solute flowing through macroscopic fractures may interact with the smaller scale microscopic fractures and pores that exist in the "intact rock blocks" separating the fractures. Understanding the interaction between the flow or fracture porosity

and the rock block matrix porosity is important because the matrix porosity, if accessible, can act as a significant storage reservoir for radionuclides (Neretnieks, 1989).

The bulk permeability of a plutonic rock mass results from the often complex manner in which individual discontinuous fractures form hydraulically interconnected networks. Flow through such networks is governed by the orientation, spacing, length and opening of fractures (Witherspoon and Long, 1987). From limited field observations and testing, it is known that these parameters are rarely uniform and that they are statistically distributed (Rouleau, 1984). Consequently, fluid flow rates and velocities in fractured plutonic rock are likely to be highly variable reflecting the large number of fracture parameters that control fluid flow.

A general and important observation regarding plutonic rocks is that structural discontinuities exist at practical scales equal to or greater than the scales of investigation. Because megascopic discontinuities are often more permeable than the rocks in which they occur, discrete characterization of these discontinuities is necessary to characterize plutonic rocks for disposal purposes (Neretnieks, 1989; McCombie et al., 1989). Efforts to characterize the hydrogeology of fractured crystalline rocks now recognize that success can only be achieved when the location and properties of controlling major fracture zones are known (Long et al., 1988).

Evidence from hydrogeologic field studies performed at all of the AECL research areas supports this thesis. At Chalk River (Raven, 1986), East Bull Lake (Raven et al., 1987), and the Whiteshell Research Area (Davison and Kozak, 1988) understanding of the groundwater flow system evolved only after major fracture zones were identified. Inspections of Canadian mines (Raven and Gale, 1985) also show that significant groundwater inflow at depth (>300 m) occurs only from major structural discontinuities such as faults, shear zones, fracture zones, and sheared dyke and sill contacts. Similar experience is available from recent detailed site characterization studies at Stripa, Sweden as part of the Site Characterization and Validation project (Herbert and Gale, 1990; Olsson et al., 1990).

Vertical Fractures

Identification and characterization of subvertical fractures and fracture zones is particularly important because such features, if present, may represent the most direct groundwater pathway between

the vault and the biosphere. Current site evaluation technology including non-intrusive assessments (i.e. air photo lineament analysis, surface geophysics, mapping, etc.) and intrusive technology (i.e. vertical to slightly inclined boreholes) are of limited use in defining the occurrence and characteristics of deep subvertical fracture zones.

The limited occurrence of permeable vertical fracture zones at AECL research areas has been inferred largely from interpretations of other hydrogeologic data (Davison et al., 1988; Raven, 1986) rather than from direct measurement. There is compelling evidence from Canadian mine inspections (Raven and Gale, 1985), and from Swedish (SKBF/KBS-3, 1983) and Swiss HLW disposal assessments (Haderman et al., 1989) that vertical permeable fractures are common in igneous rocks. Of particular interest in this regard are the subvertical permeable fracture zones or kakirites (Haderman et al., 1989) identified in crystalline rock in northern Switzerland at depths greater than 300 m only when exploratory boreholes deviated from an initial vertical orientation. The likely occurrence of undetected subvertical permeable fracture zones in igneous rocks is recognized in both the Swiss and Swedish programs with the explicit incorporation of such zones in performance assessment modelling of potential waste repositories.

The occurrence of tritium in some groundwater samples collected from deep mines in Canada (Frape and Fritz, 1987) and at Stripa (Davis and Andrews, 1990) implies that near-surface waters have rapidly migrated to depths of several hundred meters, likely along subvertical permeable fracture zones. This issue deserves the attention of AECL.

Hydrogeologic, Geochemical and Geomechanical Properties

Characterization of the hydrogeologic, geochemical and geomechanical properties of fracture zones will be crucial to accurate assessment of the barrier to radionuclide migration provided by the geosphere.

Hydrogeologic characterization must include general information on the orientation, thickness, length, continuity, and structural character of major fracture zones as well as more specific flow and transport properties such as mean groundwater travel time, groundwater pathway, occurrence of channelled flow regimes, dilution and dispersion. In identifying and characterizing fracture zones it will be important to distinguish between

groundwater flow pathways that exist at the time of site investigation and potential flow pathways that may develop as a result of disturbances (mechanical and thermal) created by the excavation and storage of waste. Potential pathways will be more difficult to identify from site characterization work because current groundwater flow is likely not directed through such pathways. Future groundwater flow possibly in response to thermal load from the waste may occur in such pathways.

Reliable predictions of radionuclide migration in fracture zones will require chemical characterization of fracture waters, fracture surfaces and the surface contact area between groundwater and fracture surfaces. Characterization of the latter is perhaps the most important and most difficult parameter to quantify at the field scale. This surface contact area will ultimately determine the amount of interaction between that dissolved radionuclides and the rock surface by controlling the available area for surface sorption and matrix diffusion. For example, if high permeability small diameter channels exist within a fracture zone, the surface contact area will be reduced and radionuclides will interact less with the rock than if smooth parallel plate flow is in effect.

Characterization of the actual matrix diffusion properties of in-situ fracture zones and rocks is also required. Matrix diffusion is theoretically a significant attenuation mechanism for dissolved radionuclides. However, field evidence of matrix diffusion is sparse, particularly for sorbing radionuclides in igneous rocks. The only reported field results are from the Stripa mine (Birgersson, 1988). These are only for conservative species and there are complications in the experimental technique that compromise the results.

Characterization of the geomechanical properties of fracture zones will also be required to predict the mechanical influence of vault construction and the heat generated by nuclear waste disposal on vault stability and groundwater flow. Such effects are likely to be of greatest significance in the vicinity of the vault. Changes in normal and shear stresses from excavation and thermal loading may result in increases and decreases in fracture permeability depending on fracture stiffness, fracture orientation with respect to the stress field, and the magnitude and type of stress changes. A complete geomechanical characterization of fracture zones and the surrounding rock is required to predict the significance of such changes.

7.3 Ability of the Geosphere to Retard Radionuclides

Among the geological considerations in siting a repository for underground disposal of high-level radioactive wastes as defined by the Atomic Energy Control Board (1987), it is required that the host rock must retard any escaped radionuclides. This implies that sorption of radionuclides by fracture minerals and matrix diffusion into the host rock should prevent discharge of any significant quantities of leached radionuclides to the biosphere. Experiments to measure solute transport in fractured rock have begun at the Underground Research Laboratory and will continue through 1995. A complicating factor in the subsurface transport of radionuclides is the occurrence of colloids (i.e. particles of 1 to 1,000 nm in size) in the fractures that may promote radionuclide migration.

Although AECL has apparently discounted the importance of colloidal transport of radionuclides in the vault, it appears to acknowledge that colloidal transport will be of critical importance in the geosphere. Recent studies by Penrose et al. (1990) in tuff at Los Alamos suggest that plutonium and americium, irreversibly bound to 25-450 nm colloids, migrated at the rate of 0.5 km/yr (although the possible role of chelating agents is not considered by the authors). Such rapid rates of migration would, if correct, invalidate the barrier concept of plutonic rocks.

Sorption

The minerals that line and, in some cases, fill fractures in crystalline rocks include hornblende, biotite, epidote, chlorite, gypsum, iron oxides, calcite, pyrite and clay minerals, such as illite (Bottomley, 1987; Ticknor et al., 1989). AECL has performed laboratory studies of the sorption of critical radionuclides on natural fracture minerals from both the Lac du Bonnet granite (Walton and Ross, 1985) and the East Bull Lake gabbro (Ticknor et al., 1989). Such experiments are significant improvements over the previous studies of radionuclide uptake on machined coupons on gabbros and granites conducted earlier in the AECL program (Vandergraaf et al., 1984; Walton et al., 1984), however they are in no way a substitute for detailed field testing conducted in-situ.

Experiments with reactive or non-conservative tracers are being undertaken at the Grimsel test site in Switzerland (Frick, Baertschi and Hoehn, 1988) and were undertaken early in the Canadian program at CRNL, although in a shallow sand aquifer

(Pickens et al., 1981). In order to demonstrate unequivocally that "the host rock and geological system ...have properties such that their combined effect significantly retard the movement or release of radioactive material" (AECB, 1987), AECL should document in the EIS their in-situ experiments of reactive radionuclide transport in granitic rock.

Matrix Diffusion

Following the pioneering work of Barenblatt et al. (1960) in the USSR, Swedish (Neretnieks, 1980) and Canadian (Grisak and Pickens, 1980) investigators simultaneously extended the dual-porosity concept of radionuclide transport in fractured rock. They showed that solute transport through fractured geological materials, such as granitic rocks, may be described by advective-dispersive transport in the fractures with accompanying diffusive transport into and out of the adjacent geological matrix. Such matrix diffusion results in substantial radionuclide retardation in numerical simulations and laboratory experiments, however, there is relatively little field evidence that demonstrates that this phenomenon is of significant importance in-situ, where channelled flow in natural fractures may limit the role of this process as an attenuating mechanism.

Furthermore, because the fracture walls of plutonic rocks are lined with secondary minerals, it is conceivable that matrix diffusion may be of limited importance in such systems. In-situ experiments are required at the URL to demonstrate that matrix diffusion is of significance in plutonic rocks and may be quantified and therefore included in solute transport modelling studies.

Colloidal Transport

The interaction of radionuclides with groundwater colloids poses special problems in terms of modelling the transport of these elements. Treating the radionuclide as a solution species without considering the colloid-bound phase has resulted in inconsistent results compared with field observations (Champ et al., 1984; Travis and Nuttall, 1985; Penrose et al., 1990). Pseudocolloids can have a net charge which in most instances is different from the charge of the radionuclide species. For example, the uptake of a cationic metal species on a clay colloid or organic particle will result in the transport of the radionuclide as a colloid of net anionic character. Alternatively, a radionuclide complexed by a

dissolved organic such as humic or fulvic acid, existing in solution as a negatively charged species, is susceptible to sorption on positively charged oxide surfaces.

The proper treatment of radionuclides in groundwater must therefore consider the chemical speciation and transport of the dissolved (solution) phase, the colloid-bound population, and the stability and mobility of the colloids in the flow system.

Table 7.3.1 is a summary of the identification procedures and characterization methods for colloids in groundwaters at various repository exploration sites in Canada, Germany and Switzerland. Detailed analyses of particle concentrations have been conducted at several locations throughout Europe, including South Terras (UK), Grimsel (CH), Markham Clinton (UK), Ispra (I), and Gorleben (FRG), under the auspices of the European Complexants and Colloids Group. The comparison of colloid concentrations shown in Table 7.3.1 is limited to the Grimsel and Gorleben waters for which detailed characterization studies exist; characterization of colloids in groundwater in the United States and Canada has not yet been published. AECL was one of the participating laboratories in the Grimsel Colloid Exercise and as such has developed the technology for sampling and characterization of colloids. The colloid concentration classification for the waters that have undergone detailed classification indicates the following order of relative concentrations: Ispra = Markham < Grimsel < Gorleben.

The conclusion that can be drawn from the Gorleben and Grimsel results is that the majority of the colloidal mass is concentrated in the 1 to 100 nanometre size range. For example, in the glacial sands at Gorleben, where the majority of particles are colloids of humic and fulvic material, most of the >1 nm colloid population in humic material is in the 1 to 10 nm size range. The fulvic material has yet to be characterized. Table 7.3.1 shows a decrease in colloid concentration of almost four orders of magnitude in comparing the 1-10 nm size fraction with the 10-80 nm size fraction. In the granite of Grimsel, the majority of the colloid population falls within the 10-30 nm size fraction. The colloid concentration decreases by two orders of magnitude in the 30-50 nm size fraction.

The chemical composition, origin, mass concentration, and surface charge density for colloids at the Gorleben, Grimsel, and Chalk River (outwash sands) sites are summarized in Table 7.3.2. At Grimsel, the colloid population is composed of illite, biotite, muscovite, quartz, Ca-silicate and iron hydroxide, and organic

TABLE 7.3.1: SUMMARY OF GROUNDWATER-COLLOID CONCENTRATIONS

Gorleben, FRG[a,1] (pt/L)	Grimsel Test Site,[b,2] Switzerland (pt/L)
$(3.4 \pm 0.3) \cdot 10^{17}$ (1-10 nm)	$5.6 \cdot 10^{13}$ (<30 nm)
$(1.9 \pm 0.2) \cdot 10^{17}$ (2-15 nm)	$4.9 \cdot 10^{11}$ (30-50 nm)
$(5.5 \pm 0.6) \cdot 10^{13}$ (10-80 nm)	$5.6 \cdot 10^{13}$ (10-80 nm)
$(1.4 \pm 0.1) \cdot 10^{13}$ (80-100 nm)	$1.6 \cdot 10^{09}$ (80-100 nm)
(3.9 ±0.7) · 10 (100-400 nm)	$4.3 \cdot 10^{09}$ (100-400 nm)
$(3.9 \pm 0.1) \cdot 10^{09}$ (400-1000 nm)	$1.9 \cdot 10^{07}$ (400-1000 nm)
Not analyzed	$4.0 \cdot 10^{05}$ (1000-10000 nm)

[a] Dearlove et al. (1989); Gohy-2227 borehole at depth 128-130 m; glacial sand, silt; samples taken by Harwell Laboratory (UK), Technische Universitat Munchen (FRG).

[b] Degueldre et al. (1989); Groundwaters from the NAGRA/PSI radionuclide migration experiment fracture; host rock is granodiorite; concentrations represent averages of reported values from participating laboratories.

[1] Photoacoustic detection of light scattering method.

[2] Various characterization techniques including Gravity, SEM, TEM, PALS.

TABLE 7.3.2: SUMMARY OF THE PROPERTIES OF COLLODIAL MATERIAL IN GROUNDWATERS FOR THREE SELECTED LOCATIONS

LOCATION	CHEMICAL COMPOSITION	SHAPE	CHARGE DENSITY	ORIGIN	MASS CONCENTRATION (mg/L)
Gorleben,[1] FRG	Predominantly humic and fulvic substances	Not reported	5.4 meq/g [a]	Local DOC source	154
Grimsel,[2] CH	Illite, biotite, muscovite, quartz, Ca-silicates, iron hydroxide, carbonate, organic material, bacteria	Variable (observation from CEA micrograph)	0.015-0.5 meq/g [b]	Erosion of fracture in-fill material	0.2
Chalk River,[3] CAN	Radiocolloids, organic material, clays	Not reported	Not reported	Reductive erosion of mineral cements, humic and fulvic material, mineral precipitates, natural clays	Not reported

[1] Gohy-2227 borehole at depth 128-130 m; glacial sand, silt aquifer.

[2] NAGRA/PSI radionuclide migration experiment fracture; granodiorite.

[3] From Champ et al. (1984); Sampling of Chemical Pit, Reactor Pit, A-Disposal, and Glass Block plumes; fine to medium sand with clayey silt interlayers.

[a] Humic colloid fraction; based on U and Th uptake measurements.

[b] Based on the size range of 40-450 nm colloids at a concentration of 200 ppb.

substances and bacteria. The bacteria represent 10^6 bact./L (0.001mg/L) in a total particle concentration of about $6x10^{13}$/L (0.2 mg/L). The mass concentration of colloidal organic carbon is 0.08 ±0.04 mg/L. At Chalk River, investigations of solubility and transport of radionuclides have provided evidence for the formation and transport of radiocolloids (chemical precipitates) of Fe, pseudocolloids (radionuclide loading on colloids) of Cs, and organically-bound Am on natural soil clays.

Determining the origin of the colloids in groundwater at the Gorleben and Grimsel sites is the focus of on-going studies. At Gorleben, the elevated DOC concentrations likely result from leaching of a local carbon source within the sand and silt aquifer. At Grimsel, Degueldre et al. (1989) attribute the inorganic colloid population to the erosion of fracture in-filling material (i.e. mylonite). At Chalk River, the colloidal material has been attributed to the reductive erosion of mineral cements and coatings, the precipitation of mineral phases in the groundwater, and naturally occurring humic and fulvic material.

The proton exchange capacity of the humic colloids (>1 nm fraction) of the Gorleben waters is 5.4 meq/g. The metal ion loading on the humic material was found to be about 20 percent of the exchange capacity or an equivalent weight in solution of about 4 mg/L. The less than 1 nm organic colloid material at Gorleben has not yet been characterized for its sorption potential. The on-going investigation at the Gohy-1231 borehole will attempt to characterize sorption on the fulvic material which constitutes the <1 nm organic colloid fraction.

Of the sites described in Table 7.3.3, the Gorleben and Chalk River studies have focused on the interaction of colloids and radionuclides as a mechanism for transport. At Gorleben, the humic colloids with a predominantly negative surface charge have sorbed up to 20 percent of their proton exchange capacity. The sorbed elements are U, Th, Hf, Zr, Fe, and several of the rare earth elements. Sorption occurs through complexing of the metals with the surface functional groups of the humic acid particulates. About 80 percent of the sorbed elements are found in the 1-10 nm size fraction, which includes essentially all of the humic material. The sorbed population represents the equivalent of about 4 mg/L. The characterization of colloids (predominantly fulvic acid) and the sorbed phase less than 1 nm size of ultrafiltration equipment has yet to be completed.

At Chalk River, the sorption of radionuclides is observed on natural clays and organic material as well as on clays whose surfaces have been modified by synthetic organics. Radiocolloids or chemical precipitates are also proposed. The surface charge on the sorbing colloids (non-precipitate forms) is predominantly negative. Sorbed elements include Cs, Co, Nb, Zr, Ru, Sb, and the rare earths, Ce and Eu. Approximately 25 percent of the Cs load in the Chemical Pit plume was determined to be in colloid-bound form (Champ et al., 1984).

TABLE 7.3.3: EVIDENCE FOR RADIONUCLIDE-COLLOID INTERACTION

LOCATION	NATURE OF COLLOID	SURFACE CHARGE	SORBED ELEMENTS	SORBED CONCENTRATION	COMMENTS
Gorleben, FRG	Humic (>1 nm size), fulvic (<1 nm size) solids	Predominantly negative	U, Th, Fe, Hf, Zr, rare earths (on humic material)	1.08 meq/g or 4 mg/L	(80 ±6) % of sorbed elements are on the 1-10 nm humic material
Grimsel, CH	Silicates, iron hydroxide, carbonate, organic material, bacteria	Mixed[1]	U, Ra	(U only) 7.5 ±2 % and 25 ±4 %	None
Chalk River, CAN	Clays, chemical precipitates, organic material	Predominantly negative[2]	Cs, Co, Nb, Zr, Ru, Sb, Ce, Eu[3]	25 % Cs[4]; remaining elements trace	Interference of synthetic organics on formation of colloids and sorption noted

[1] No detailed characterization studies completed to date on nature of charged surfaces.

[2] By inference from transport observations; synthetic and natural organics also found to complex and transport radionuclides.

[3] Either sorbed to natural colloids or as colloidal precipitates.

[4] Of the total Cs concentration in the Chemical Pit plume, about 25 % is in particulate form.

From the limited evaluation of the sorbed phase, sorption of U and Ra was noted on the colloids from the Grimsel waters. Given the mixture of colloid material including clays, metal-oxides, and natural organic material, both positive and negative surface charges would exist and would support the sorption of metals and anionic complexes (e.g. metals complexed with dissolved organic carbon). From the results of two independent uranium analyses of colloidally-bound uranium, from 7.5 ±2 to 25 ±4 percent of the total uranium is in bound form. Questions regarding the sorptive loss on sample containers of the relatively small concentration of organic colloids precluded their study (Delgueldre et al., 1989).

The stability of the colloid phase must be associated with the evolving groundwater chemistry along the flow path. Solid samples collected from the same depth as groundwater samples could yield some of the information needed to model the interaction of colloids with the matrix and fracture surfaces (Dearlove et al., 1989). Characterization of the source and supply of colloid material is also necessary to quantify the colloid population and to understand the significance of colloid transport over time.

7.4 Verification and Validation of Geosphere Models

AECL proposes to demonstrate the post-closure performance of a nuclear waste repository against safety criteria using its Systems Variability Analysis Code - SYVAC (Dormuth, 1989). A third-generation version of this code SYVAC-3 is currently under development. SYVAC is a systems analysis computer model with three submodels describing processes occurring in the vault, geosphere and biosphere. The geosphere model is called GEONET and contains several 1-D, steady state, porous media equivalent, groundwater flow pathways (Wuschke et al., 1985). GEONET applications will be based on results from the more complex, research-level, geosphere model MOTIF (Lyon, 1984).

Because SYVAC is a computer model, AECL must demonstrate that SYVAC has been sufficiently verified and validated for use in safety assessments of a nuclear waste repository. Only after such a model is verified and validated can it be applied in safety assessments.

Verification and validation of performance assessment models may be one of the most important and yet difficult issues to be addressed in AECL's EIS. Because the final quantitative assessment of safety for a nuclear waste repository will be based on SYVAC, the ultimate acceptability of the concept may be based on the acceptability of SYVAC. This has been recognized by the Technical Advisory Committee (TAC) on the Nuclear Fuel Waste Management Program in almost every annual report. TAC has indicated that they support the SYVAC approach "provided the conceptualization of the system, events and processes including all of their component parts and parameter distributions have validity" (Shemilt et al., 1989).

The following sections provide a technical summary of several key issues related to verification and validation of the geosphere

models to be used by AECL. These issues include verification, validation, GEONET simplifications, parameter uncertainties and process uncertainties.

Verification

Verification is the relatively straightforward process of obtaining assurance that a computer program correctly implements a conceptual and calculational model. It is usually done by comparing results calculated by the code in question with known analytical solutions or with results calculated by similar codes. Related components of a verification process include a well documented quality assurance program for models, input data and scenario identification (McCombie et al., 1990). AECL should document their verification exercises in the EIS as well as their software quality assurance program which has been scrutinized by TAC (Shemilt et al., 1989).

Verification is relatively easy to demonstrate and AECL, through their involvement in various intercode comparison projects such as HYDROCOIN, INTRACOIN, INTRAVAL, CHEMVAL, and PSACOIN, is making significant efforts to verify the component modules and overall performance of SYVAC. The PSAC (Probalistic Safety Assessment Codes) user group (Thompson et al., 1989) is the most relevant intercode comparison project to verify SYVAC. The PSAC users group has identified several technical issues of concern including statistical sampling strategies and assessments of convergence, presentation of results from PSA codes, derivation and justification of submodels used in PSA codes, scaling effects and use of non-dimensional variables and spatial variability and uncertainty (Thompson et al., 1989).

Validation

Validation is the process of ensuring that a model, as embodied in a computer code, is a sufficiently correct representation of the process or system that it is intended to simulate. This implies that the conceptual model of the code includes all the essential features and processes of the real world. Ideally, validation involves comparisons of direct observations with results calculated by the code. Because of the time and physical scales of most repository models, this approach is not possible and "validation remains the key issue facing performance assessment" (McCombie et al., 1989). A particularly credible validation of a model would be to show that it reproduces the observed behaviour of a natural analogue structure or process.

Model validation is very difficult for models like MOTIF and may verge on the impossible for SYVAC. In their EIS, AECL should address each of the following issues relating to validation of geosphere models.

GEONET Simplifications

For analytical expediency, the GEONET model (Wuschke et al., 1985) is based on a series of one-dimensional flow paths for radionuclide migration. Groundwater flow in each of the flow segments is calculated based on equations describing fluid flow and solute transport in an equivalent porous medium. These are significant simplifications to the complex three-dimensional processes of groundwater flow and solute transport that occur in plutonic rocks. AECL must clearly demonstrate that the GEONET model will adequately represent the essential physics of three-dimensional solute migration and the complete range of possible behaviours at field scale. This may be complex in light of the likely occurrence of channelled flow regimes in natural fractures and the fact that it is not yet known at what scale it is possible to represent transport processes by an equivalent porous medium model (Witherspoon and Long, 1987).

Parameter Uncertainties

GEONET and SYVAC utilize probability distributions functions (PDFs) for input parameters such as hydraulic gradient, hydraulic conductivity, porosity, dispersivity, and distribution coefficient. From these inputs, the models produce PDFs of the maximum annual dose equivalent. GEONET results can only be reasonable if the input parameters are reasonable. Errors in input parameters are recognized as one of the main sources of errors and uncertainty in the prediction of the geologic behaviour of a nuclear waste repository (de Marsily, 1989).

There will also be uncertainties in hydrogeologic input parameters as a result of natural spatial variability, measurement uncertainties and test interpretation uncertainties. The use of PDFs in SYVAC in some ways accounts for this uncertainty, however AECL must demonstrate the basis for selection of input PDFs to GEONET and the relative weight given to the results of laboratory and field tests and expert opinion in determining the PDFs.

An important issue related to parameter uncertainty is the way in which AECL will address the variations in hydrogeologic conditions over the 10,000-year time frame of performance assessment. Geologic and hydrogeologic systems relevant to radioactive waste disposal assessments are not static but slowly evolve over periods of time similar to those considered in waste disposal. In the 10,000-year period, transient surface processes such as glaciation, and slowly evolving processes such as rock creep and chemical precipitation will result in changes in input parameters to systems analysis models such as SYVAC. These time dependent processes may render models such as SYVAC useful only for periods of some hundreds of years (Chapman, 1989).

Process Uncertainty

SYVAC and other systems variability analysis models are principally parameter uncertainty analysis tools. Risk calculations derived from such models do not take into account uncertainty in conceptualizations and processes. Process uncertainty in the complex geosphere system, particularly over the long timescales involved in performance assessment (i.e. 10,000 years) is likely to be of great importance. Specific areas where there is a significant level of process uncertainty include:

- coupled thermal, mechanical hydraulic, and chemical processes in the immediately vicinity of the vault;
- groundwater flow and radionuclide transport in the geosphere; and
- colloidal and microbially-assisted transport of radionuclides in the vault and geosphere.

Section 7 References

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8.0 BIOSPHERE

A primary objective of AECL's disposal concept assessment is to demonstrate to the public that high-level radioactive waste can be handled and disposed of with an acceptable and minimal risk to the environment. In this chapter, we consider issues relating to the biosphere, defined here as the physical-chemical environment which contains and supports living organisms. In accordance with Environment Canada's mandate, the discussion here will include living organisms and the environment on which they are dependent. Consequently, the biosphere assessment must consider the potential impacts to both abiotic and biotic components of the environment arising from pre-closure and post-closure activities, or accidental releases of material.

In AECL's disposal concept, predictions of impacts and subsequent risk to the biosphere are anticipated to be calculated through the use of computer simulations. In developing the biosphere model, certain factors must be considered:

1. risks to sensitive or valued biota must be specifically estimated, and it cannot be assumed that adequate radiological protection of the entire biosphere will occur indirectly through protection of man;
2. environmental effects from non-radiological and radiological contaminants must be calculated as well as effects associated with physical disturbance;
3. although detailed monitoring plans may not be finalized until after site selection, general approaches and ecological endpoints of interest (e.g. population decline, loss of diversity) can and should be defined, along with how they will be monitored at the concept stage; and
4. the biosphere model needs to explicitly account for the influence of microbes, such as bacteria, which can have a potentially significant effect on the mobility of radiological and non-radiological contaminants.

These considerations can be resolved into a number of key issues which should be incorporated into any biosphere analysis employed:

- characterization of transport of radiological and non-radiological contaminants through environmental pathways;
- definitions of appropriate ecological endpoints and development of a methodological framework for their

prediction and measurement;

- characterization of "reference environments" on the basis of selected physical, chemical, and biotic attributes related to ecological endpoints of interest; and
- evaluation of physical, chemical and biological influences on the mobility of radiological and non-radiological contaminants through the biosphere.

These issues are discussed in greater detail in the following sections.

8.1 Fate and Effects of Contaminants

The rates of transport of radiological and non-radiological contaminants through the food chain, and their possible effects on living organisms, should include the following in both pre-closure and post-closure analysis:

1. estimates of the amounts, forms, and sites of escape from the disposal facility of all potential contaminants;
2. predictions of the physical-chemical and biological transformations which may cause alterations to transport processes in the environment;
3. studies involving the exposure and responses of one or more representative indicator target organisms to representative potential contaminants; and
4. estimates of the responses of populations and communities to these contaminants or combinations of contaminants.

Estimating the amounts and chemical forms of possible contaminants released from the high-level radioactive waste storage facility is a prerequisite for evaluating potential biological and environmental harm. It is also important to understand how these contaminants are chemically altered as they move through the abiotic and biotic components of the ecosystem. There are predictive models, such as MINTEQ (U.S. Environmental Protection Agency) and GEOCHEM (University of California Riverside), which permit computers to simulate chemical changes in soil and water. It is also possible (in certain cases) to determine the concentration and biological activity of different forms of chemical contaminants in water, air, soil, and sediment (Sposito, 1986). Pre- and post-closure analyses should include modelling of

contaminant releases to the environment in both routine and accident-related amounts, using models based upon fundamental principles.

Concentrations of potentially harmful substances are often judged according to an acceptable threshold exposure level, usually based on effects or risks after chronic exposure. Environmental and health protection agencies (including, for example, the U.S. EPA and the U.S. Food and Drug Administration) have established acceptable exposure levels based either on the concept of a threshold for effect, or on the concept of an acceptable risk threshold. The latter concept is appropriate for contaminants which act in a stochastic manner. Toxic effects and risks must be estimated, whether or not regulatory criteria exist (e.g. U.S. EPA, 1989).

Biological concentration occurs when residues are picked up directly through the skin or intestinal or respiratory surfaces. Biomagnification - or food-chain concentration - occurs when one organism feeds upon another and accumulates a greater concentration of contaminant in small incremental doses. Both processes can lead to increasing quantities of contaminants in organisms towards (or at) the top of a food chain. AECL should specify, in its biosphere model documentation, the bioaccumulation factors used and the basis on which they were selected.

Because it is difficult to generalize from particular systems (Schoener, 1989), biomagnification of contaminants should be evaluated in simple food chains of the local environment. Data from field experiments are needed to examine the movement and transformation of substances over more than one level of each food chain. Several laboratory test models have been developed, though results are often difficult to extrapolate to actual natural systems (Metcalf, 1974). The synergistic effects of combined toxicants (that is, when the effect due to more than one chemical is greater than the sum of each chemical's individual effects) should be included in the analyses. Acceptable threshold concentrations may be determined by studying the interactive effects of combined toxicants in simple food chains, taking into account the problem of biomagnification and the mode of action, and can be used to calculate the risk associated with chronic exposure at several trophic levels. Where exposure to one or more chemical compounds or radionuclides occurs, the total or combined effect must be evaluated.

Data from field and laboratory tests can be combined to derive time-dependent models that estimate effects of contaminants on single species, and species changes in resistance or susceptibility to chronic exposure. Effects considered can vary from simple measures of population size or density to measures of change in species composition or trophic structure in multi-species (or multi-population) communities. The inherent high level of variability in these parameters makes it very difficult to predict effects. In addressing these areas, AECL should clearly state the uncertainties involved and the ecological significance of these uncertainties.

The release of radiological and non-radiological contaminants can bring about changes in the biosphere. Generally, exposure to contaminants or other forms of stress simplifies ecosystem structure and modifies the ratio of gross production (by plants) to total ecosystem respiration (of both plants and animals). Another potential effect is a trend from highly specialized species to generalists (with regard to feeding behaviour, habitat preference, and so forth), and a reduction in species diversity (generally the number of species and their relative abundances). Any stress-related changes in ecosystem structure predicted by AECL should be correlated to the time-dependent aspects of contaminant concentration in the environment and other stress-related events. Ecosystems are dynamic and can undergo natural evolutionary changes that must be distinguished from contaminant-related changes. It is important that AECL explain this and the degree to which the disposal site will contribute to these changes.

8.2 Identification of Ecological Effects and Endpoints

The environmental impact assessment process is an objective analysis conducted to predict and quantify likely effects of a proposed action and various alternative actions. Impact assessments are based on experimental data from laboratory and field studies and on technical judgements by various social, economic and environmental experts. Technical judgements are often based on a blend of both quantitative modelling and qualitative predictions. Both types of predictive techniques may be needed. This is especially true for environmental matters associated with disposal of high-level radioactive waste (Winograd 1990). Given the uncertainty in the impact assessment process, there is a need to assess the adequacy of methods that will be used to determine predicted impacts. More specifically, there is a need to evaluate the adequacy of ecosystem modelling as a tool for judging impacts.

A variety of model validation techniques can be used, but none of these provide proof of the nature of future consequences. Given the possibility that impact predictions based on modelling may be incorrect, to test how close predictions are to reality, adequate validation may require monitoring of actual effects in the short-term or natural analogues for the longer term. If monitoring is adopted as one acceptable method for validation, the monitoring program must be integrated with the modelling study; data for both purposes should be collected at the same time for description of baseline conditions and for ecosystem model input. An integrated monitoring program would address five components: study design; data acquisition methods; ecosystem modelling; impact recognition; and acceptability of change.

Study Design

AECL should provide a framework upon which a monitoring program will be based at the concept stage. A monitoring program should allow comparison of baseline, pre-closure and post-closure conditions at the development site against conditions at a control site. The details of how such comparisons should be conducted must be worked out in advance by a team of statisticians, ecologists, toxicologists and radiation specialists. Decisions should be made in the design phase about impact hypotheses to be tested, descriptors that will be used in addressing hypotheses, significance levels, sample sizes, and number of replicates required to detect certain degrees of change over time. Definition of domain is a critical aspect of the monitoring plan. On assessing these aspects, the proponent should review ecological studies carried out in environments where levels of ionizing radiation are naturally or have been accidentally or intentionally increased above natural background levels in order to assess the size of an appropriate monitoring area for a reference system. It is, however, recognized that many details of design will be site-specific. The environmental monitoring plan should include the concepts on which a site-specific baseline study will be designed once a site is selected. Both literature and site information on variability in reference environments will be useful for optimization of the plan.

Data Acquisition Methods

The monitoring program must be accompanied by a detailed procedures manual outlining the study design, the parameters to be measured,

and the methods that will be used to gather data and produce information. Without documentation of methods and rationale, the likelihood of similar types of data being collected in the future is low. This does not imply techniques should not be updated, but only that, when they are, the relationships between the old and newer proposed technique or approach are fully understood such that comparative information transfer is possible.

Ecosystem Modelling

Given that ecologists know relatively little about population regulation and even less about ecosystem function, ecosystem models may be of limited use in prediction of ecosystem changes. However, ecosystem models can be used to estimate the consequence of an event to different species and life stages. The consequence of various activities or contaminant releases must be compared to known effect levels in order to infer potential population impacts. AECL should provide a clear and concise description of events or activities which may be expected to cause ecosystem effects and compare these to predicted effects of the development, operation and closure of the waste management facility.

Impact Recognition

Scientists know that an increase in ionizing and, to a lesser degree, non-ionizing radiation may cause mutation rates to increase. This may manifest itself in somatic diseases or in the form of genetic load. The effects of moderate to high doses of ionizing radiation on individuals (e.g. time to death or cancer risk) are known and have been described. There is less known about low (sub-lethal) doses and possible long-term effects in animal and plant populations. Theory suggests that an increase in dominant gene mutations would be selected against in one or two generations. However, selection works slowly to remove mutation of recessive genes (Mather 1973); thus, genetic load can accumulate. Often populations will compensate for increased genetic load (e.g. by increased fecundity) so that population density effects may not be detectable. AECL should consider measures of heterozygosity or genetic load in natural populations as a useful monitoring tool.

Changes due to possible increases in low-level exposure to chemicals or radiation could possibly be detected as an increased death rate over several generations (due to either genetic load or disease induction) as a reduction in population density. Reduced

population density may influence ecosystem functions such as productivity and the various efficiency ratios commonly used to study ecosystems. The likelihood is low that changes due to low levels of exposure to chemicals, radiation or other environmental stresses could be detected via changes in the various efficiency ratios used to assess ecosystems. The degree of certainty that change can be detected is greater the closer the measurement is to the primary influence of exposure and the more immediate the effects (e.g. shorter life, reduced fertility, embryonic mortality, reduced growth). AECL should evaluate the feasibility of monitoring these endpoints for a reference population, although population and community consequences are probably more relevant to societal ecosystem values.

Acceptability of Change

There is a need to determine at what level changes in biological systems are detectable and at what level detectable changes become unacceptable. The issue of acceptability is perhaps the crux of the entire environmental impact assessment process for it forces the question: what is an acceptable degree of change to today's society, and is the same likely to be acceptable to future societies? The answer to this question is not an easy one, for it not only involves today's and future societies, but also the obligation of today's society to deal with nuclear waste in a responsible manner so future societies will know the who, where, how, why and when of waste disposal. AECL must provide an explanation of the degree of environmental change that may result from the development, operation and closure of its high-level waste disposal facility, and a discussion as to its level of acceptability.

8.3 Attributes of "Reference Environments"

Because the Ontario portion of the Canadian Shield in which plutonic rock outcrops covers an area of approximately 674,000 km^2, there are many distinct terrestrial and aquatic ecosystems and potential habitats for rare, threatened, endangered, or endemic species. While recognizing that many of these attributes are site-specific, conceptual evaluations can nonetheless be used to identify ecosystems, types, or reference environments. However, it is essential that AECL include the definitions applied to the reference environments. Careful selection of properties should permit the selection of a control site for temporal comparisons

which recognize the continual changing nature of natural systems. Properties which can be measured at one hierarchical level (such as diversity, stability and resilience) allow evaluation of impacts on the system as a whole.

Diversity needs to be evaluated for structure and function. Structural diversity incorporates numbers of species and relative abundances. The measures chosen to estimate diversity must be appropriate to the type of fauna and flora being discussed. For example, the underlying assumptions of the Shannon-Wiener and Bruilloin diversity indices are not met for aquatic invertebrate data (Shepard 1984) but may be appropriate for terrestrial vegetation. Functional diversity can be measured by food-web complexity (the number of energy paths among all trophic levels). The relation between food-web complexity and ecosystem stability has been modelled theoretically by May (1981). Similarly, there are several proposed measures for stability and resilience.

The choice of factors which are used in estimating long-term biospheric impact potential should recognize that the degree of impact from the same factor may be very different in different reference environments (i.e. heat transferred from the proposed storage vaults to the surface). In more southern areas of Canada, the projected 10° C ground surface temperature rise over time may not be ecologically significant; in more northern regions (especially in an area of permafrost) this physical factor may be extremely significant. Selection of the most suitable factors for the disposal concept needs to be discussed in terms of the underlying assumptions, the practicality of measuring the parameters, and an assessment of whether or not our ability to measure these parameters is of significance to society at large.

8.4 Model Parameter Values

Generic parameter values for both aquatic and terrestrial biospheric transport models can be found in IAEA Safety Series No. 57 (IAEA 1982) and USNRC 1.109 (1977). More detailed review and recommendations for transfer factors such as soil-to-plant transfer coefficients can be found in Ng et al. (1982). Generic values are usually considered adequate for use as parameters in biospheric transfer models for order of magnitude calculations when site-specific values are not available.

Environmental factors can have a significant influence on parameter values. For example, the bioaccumulation factor (BF) for cesium in

freshwater fish, can be influenced by the potassium concentration in water. The BF for ^{137}Cs in fish can vary from 4×10^2 in a eutrophic (i.e. highly productive) environment to greater than 10^5 for oligotrophic environments (Vanderploeg et al. 1975). The generic, or default, BF for ^{137}Cs in freshwater fish is 2×10^3 (IAEA 1982); therefore, because of the range of BF values, it is important to have site-specific data for this model parameter, or to apply the highest and hence most conservative value.

Another parameter of direct relevance which can vary significantly is freshwater fish consumption by humans, which can range from an average of 0.54 kg/yr to 59 kg/y (Rupp 1980). Variance in dietary habits could be especially true for Canadian human populations because of the many cultural differences that may be found in reference environments. Not only does the dietary habit vary from population to population, but it can change over time within a population. This variability could influence long-term predictions. Because human dietary habits can have a profound influence on the potential radiation dose to individuals and can change significantly over time, conservative values should be used in model calculations unless otherwise justified.

There is, however, a considerable amount of environmental and geochemical data available in the scientific literature that can be assembled and used with relative confidence to provide estimates of parameter values for biospheric models for the assessment of the Canadian disposal concept. A few examples of the types of available information are: radioactivity in the Canadian aquatic environment (NCRCC 1983); geochemical pathways in small Canadian Shield lakes (Hesslein and Slavicek 1984); effects of acidification on mobilization of heavy metals and radionuclides from sediments (Schindler et al, 1980); and radionuclide levels in fish near uranium mines and mills (Swanson, 1983).

8.5 & 8.6 Mobilization of Radionuclides and Metals by Microbes

Microorganisms can affect the mobility of metals (and radionuclides) by several mechanisms (Brierley 1990, Williams and Silver 1984, Silver and Misra 1988). Microorganisms can:

- enzymatically transform metals (by oxidation, reduction, methylation or demethylation) which affects their solubilities and vapour pressure;
- metabolize metal complexes, such as those of nitrate and sulphate, releasing the metal to solution;

- actively or passively affect the uptake (bioaccumulate) of metals, which can then be transported by motile or dislodged bacteria;
- release metabolites that complex with metals (e.g. chelators); and
- modify the geochemical environment (e.g. pH) which affects metal speciation and solubility.

Microorganisms possess elaborate metal detoxification mechanisms (Williams and Silver 1984, Silver and Misra 1988, Robinson and Tuovinen 1984) which allow them to survive and function in metal-containing environments. Their activity could promote the bioavailability of metals and radionuclides. Various mechanisms are discussed below as examples.

Autotrophic acetogenic bacteria are capable of greatly increasing the solubility of uranium by oxidizing it to the hexavelant ion (McCready and Gould 1990). Metallic oxides can be used as electron acceptors and subsequently be reduced to divalent ions under anaerobic conditions (Francis and Dodge 1988). The divalent ions have solubilities orders of magnitude greater than the metallic oxide precursors. Barium and radium sulphate sludge wastes can support the growth of sulphate reducers without the addition of nitrogen and phosphorus nutrients (Fedorak et al. 1986). Sulphate reducers activity was shown to influence the release of $^{226}Ra^{2+}$ into solution from barium and radium sulphate with the subsequent level of radioactivity reaching 400 Bq/L after ten weeks with no apparent effect of microbial activity (Fedorak et al. 1986). One of the most potentially troublesome problems is the mobility of ^{99}Tc which is solubilized if oxidized and effectively immobilized if reduced to the sulphide (Henrot et al. 1988). Mixed anaerobic cultures can reduce pertechnetate and enable its association with organics in the environment. Depending on what organics are present, this may immobilize it or cause it to move more rapidly.

Methylation of mercury has been widely documented (Williams and Silver 1984, Silver and Misra 1988, Robinson and Tuovinen 1984) and is ubiquitous in nature. This mechanism creates a volatile form of mercury which is less toxic to procaryotes but is extremely toxic to eucaryotes. Methylation of Sn, Se, As, Te, and Pb has been readily demonstrated and is commonly recognized as a problem at many contaminated sites. In general, anaerobes are the most effective methylators, but methylation can also occur in aerobic environments. Demethylation reactions also occur and the manipulation of the vault microbiota could be utilized to help control migration to the geosphere.

The cell walls of microbes and their extracellular polymer secretions contain complex polysaccharides with both amino and carboxyl moieties and the major charged groups. There are more negatively charged groups on the microbial surfaces so cations like metals are more likely to be found than anions (McLean and Beveridge 1990, Myers and Beveridge 1989). The binding of some elements on to the cell wall can enhance the uptake of these elements (Geesey and Jang 1990). The exopolymers, which are rich in uronic acids, are powerful chelating agents for metals (Brierley 1990) and, after being shed from the originating bacteria, can chelate metals, in the absence of the bacteria.

Bacteria can induce precipitation or dissolution by excreting a substance that chemically reacts with the metals. For example, Fe_2O_3 and MnO_2 can be solubilized directly by enzymatic actions, whereas, CdO, CuO and PbO are solubilized indirectly by the production of reductive metabolites (Francis and Dodge 1988). Microorganisms release organic acids (e.g. dicarboxylate, 2-ketoglaconate, polyhydroxy acids) and phenolic compounds (e.g. protocatechuate, salicylate) which are effective heavy metal chelators which can promote metal transport in soils (Francis 1984).

Siderophores are proteins which allow microorganisms to uptake essential metals, such as Fe, at low concentrations and are often produced when the microorganism is stressed in a low nutrient environment. Siderophores are usually metal-specific but will also bind to other metals with various degrees of affinity. However, when siderophores react with other metals the resulting complex may not be recognized and taken up by the microbial transport system (Clark et al. 1987). This mechanism is one strategy by which microbes protect themselves from toxic metals. Since there are chemical similarities between Fe(III) and Pu(IV) and between Th(IV) and Pu(IV), it is possible that iron siderophores will form soluble complexes with Th and Pu.

Intercellular accumulation of metals is a process by which bacteria can affect metal migration in rock, soils and sediments. The initial binding is usually to the cell walls but the accumulation into the cells is an active process (Brierley 1990). Uranium, radium, and cesium can accumulate in common bacteria like *Pseudomonas aeruginosa* to the extent that they seriously interfere with cellular processes and are readily seen in the electron microscope as dense intercellular deposits (Strandberg and Arnold 1988). Deposits of uranium can reach 10-15% of the dry cell weight (Strandberg et al. 1981). The bound metals can be transported by

either motile microorganisms or by the detaching and adhesion of non-motile microbes. There is evidence that the hydrophobicity of the cell wall changes in response to the activity to the microorganism. In locations were conditions favour growth, the hydrophobicity of the cell wall increases and allows adhesion onto surfaces. Hydrophobicity decreases during periods not favouring growth, allowing the microorganism to detach from the surface and be transported by water to more favourable locations (van Loosdrecht et al. 1987a, van Loosdrecht et al. 1987b).

Microbial activity is primarily responsible for the most frequently observed changes in the geochemistry and redox conditions of groundwater and soil (Champ et al. 1979). *Thiobacillus ferroxidans* is an example of a microorganism that can greatly affect the pH of groundwater. This microorganism can generate energy by the oxidation of reduced sulphur (usually sulphide) or ferrous iron in the presence of oxygen (i.e. it is an autotroph) producing low pH water (acid mine drainage). Since the solubility of both stable and radioactive elements is largely determined by the Eh/pH regime, then the activity of groundwater and soil microorganisms could have a profound impact on the containment and mobilization of these compounds.

The best studied examples of microbial affect on metal mobility are the elaboration of hydrogen sulphide, which can form metal sulphides which are essentially insoluble in many cases. Many metallic ores are biogenic sulphides. Another less well-studied chemical modifier is phosphate which can also form essentially insoluble complexes with metals. In reverse reactions, bacteria, particularly the acid-forming bacteria, can oxidize metal sulphides to much more soluble sulphates or various intermediate oxidation states. Phosphatises yield phosphates from organic esters and can be utilized to effectively remove 90% of the uranium nitrate from a mM solution flowing at 1.25 ml/min in the presence of biofilms of *Citrobacter sp.*[19] (Macaskie and Dean, 1987).

Mobilization and demobilization of both stable and radioactive elements between the vault and the biosphere, as well as in the biosphere, will be greatly influenced by the activity of microorganisms. It is important to understand which microorganisms and their affiliated activity will be operational in environments in which the microorganisms and stable and radioactive elements come in contact. The Ubiquity Principal states "...all types of bacteria are available at all times everywhere...". Hence, the available nutrients and type of reduction-oxidation couples will determine which type and level of microbial activity will dominate

and ultimately affect the fate of released actinides and metals. AECL, in its assessment, must pay special attention to microbial processes and their role in controlling environmental distribution of both stable and radioactive elements.

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9.0 SOCIAL ISSUES AND PUBLIC PARTICIPATION

AECL's concept for permanent disposal of high-level radioactive waste will mean a substantial change in the Canadian social environment with respect to nuclear power. Despite the concept focus on radioactive waste disposal, the concept review is likely to have an impact on the behaviour of individuals, interest groups and communities regarding nuclear wastes, their perceptions of public health and safety, and their commonly held values about nuclear power. These factors will affect the public's participation in the concept review, in the siting process and their actions following completion of the EIS. Social impacts will play a central role in the decision whether to accept the disposal concept proposed by AECL or to examine alternatives.

9.1 Information Availability and Review Time

Dealing with the social impacts of an radioactive waste facility involves making an unknowable (uncertain) risk knowable, or understood, and building trust that information is readily and fully available, complete and accurate.

Uncertainty of any kind has been found to increase perceived risk, to increase uncertainty in risk estimates or impacts, and is especially difficult when there is disagreement among members of the scientific community about the degree of risk and the expected impacts of the facility.

The process of public participation has, at its centre, the objective of increasing the knowledge of the project and its impacts, and in increasing trust in the information and in the project proponent. This is partially accomplished by adequate time for the review of documents, full disclosure of the uncertainties inherent in the estimation of risks and impacts, and accountability to those who participate for provision of information with adequate time for review.

The proponent should make immediately available to scoping participants a list of all research and development studies, scientific and technical support documents used to prepare the concept EIS. The documents should be available as part of the EIS review no later than six months prior to the EIS submission date and the review period for the EIS should be a minimum of eight months before hearings. AECL should also present annual assessment briefings for new research, development and supporting documents.

The EIS to be prepared by AECL will be based on over ten years of research and development on the nuclear fuel waste management and disposal concept. The magnitude, detail, scope and complexity of the EIS will be such that adequate review time must be made available to both the Panel and the intervenors. In order that members of the public have an opportunity to meaningfully participate in setting the scope of the EIS, it will be necessary for participants to review the existing documents which provide details of AECL's proposed concept, and other available documents which explain alternative concepts, and their environmental, social and economic benefits and costs. In developing guidelines for other environmental assessments involving large projects or policy issues, document review has required both a means of providing access to the relevant information and the allocation of sufficient time in the scoping process to allow for a review of the information.

The suggested review period of 90 days prior to the hearings appears inadequate for a comprehensive review. Furthermore, there is a perception that AECL is several years behind in publishing the basic scientific and technical work on the concept that they have already completed. This work must be published as soon as possible.

9.2 Compensation

Acceptance of a facility that creates risk and other social or economic costs depends to some extent on the degree to which the imbalance between benefits and costs to local residents has been redressed. A radioactive waste disposal facility, like other high-hazard facilities, is often viewed as structurally unfair to those who live in its vicinity because it generates broad societal benefits but local costs, both real and perceived. The fact that there are global benefits does little to offset local risks. In order to address that unfairness, it is necessary that the EIS process involve a method for exploring compensation with local communities, preferably at an early stage in siting when several sites can opt not to accept. It should also be clear that the redistribution of benefits is often not sufficient in siting a risk-generating facility without some sharing of control of the operation. Risks may, to some extent, be mitigated by design or operational changes at the facility, but it will also be necessary to develop a method of sharing control of the facility with those who are potentially affected by it. Sharing of control linked with compensation for dis-benefits are parts of a method for dealing

with social impacts of a disposal facility and the method should be specified.

9.3 Site Selection

Beyond the conceptual issues in the first stage of the EIS, the role of the public in site selection will be a central concern. it will be important to clearly indicate how the public will be involved in setting the criteria for site selection, for screening of a number of site choices to a smaller set of candidate sites and in making the selection. In particular, it will be important to know whether a large set of reasonably acceptable sites will be considered together with their social, economic and risk impacts, or whether the EIS process will attempt to identify one optimal site.

Furthermore, it will be a central question whether a large set of reasonably acceptable sites will be approached by the proponent to determine the willingness of each community to accept the site, or whether one optimal site will be selected before its community is approached.

With several candidate communities, each has a greater opportunity to choose not to accept the facility. Each also has the opportunity to compare risks and benefits that would affect other communities. A greater degree of fairness is achieved if there are several candidate communities and each has an opportunity to examine the risks and benefits associated with the facility.

A process of community contact and exploration of risks and benefits with each should be developed and discussed as part of the concept stage.

9.4 & 9.8 Risk Acceptance

The disposal facility concept decision will be based on an estimate of risk acceptability. National levels of risk acceptance (the risks Canadians typically assume) can be estimated based on historical records of risk behaviour.

These levels of risk acceptability are not likely to be consistent with risk levels accepted in the reference siting areas, nor are the types of risk generated by the facility necessarily preferred by residents in those areas. There is likely to be considerable

cultural and social variation in the willingness to accept risk that national risk statistics may not reflect.

The cultural and regional variations in risk acceptance should be examined as part of the social impact assessment of the concept. Communities may have different responses to risk and those responses will figure prominently in the siting process. This is also likely to be significant in the case of native communities in the reference siting areas. Those communities may be averse to specific types of risk or have different levels of risk acceptance than non-native communities.

A method of community consultation about the types of risk that are acceptable and the levels of risk that might be tolerated among a number of candidate sites should be outlined as part of the public participation process for the concept EIS.

9.5 Broad Social System Effects

The social impacts stemming from the concept are focused at the national level and are broad in nature because specific sites are not identified nor are there specific communities that might be affected. Consequently, concept impacts will tend to reflect widely held values and perceptions about what constitutes an acceptable risk to human health and the natural environment, and what level of public safety should be achieved by the disposal concept. Similarly, there are likely to be differing cultural and regional impacts of the concept because of the great variation in views about nuclear wastes among cultural and regional populations in the areas (reference environments) likely to be affected. A sufficient review of the proposed concept will require both an opportunity for the review and discussion of impacts by cultural, aboriginal and regional populations and a review of the impact of the concept on commonly held values, the acceptability of risks and the desired levels of public health and safety to be achieved by the concept.

9.6 Evaluating Social Impacts

The concept review must also include an outline of the process for siting the facility and estimating its narrower, site-specific social impacts. It is crucial, at the concept stage, that the process for predicting and evaluating social impacts of the facility at a number of sites be clearly specified and acceptable.

Each candidate region will have an interest in knowing what social impacts will be examined in the siting process, and how each impact will be valued in the siting decision. It is important at the concept stage that the siting process and the manner in which social impacts will be valued in the decision process are explained.

9.7 & 9.9 Public Participation

The objective of the public participation component of the concept review is to reach a consensus with the public participants (community and aboriginal groups, environmental and public interest groups, local governments and individuals) to pursue the disposal concept to the siting stage. There are difficulties inherent in a national process of public participation for a large and technically complex issue such as radioactive waste disposal that the participation process must address.

There is a problem in informing and involving the morally relevant communities (those cultural groups or communities that might be affected by the concept) in the public participation process. The process that uses newspaper notices and scoping meetings in major cities may not adequately inform or involve all morally relevant parties.

There is also a need to support the participation of groups and communities that might be affected both in reviewing the documents and in participating in the concept review. It is necessary in a consensus-seeking process that participants have the means and the opportunity to be informed and to participate in a discussion of concepts at this stage.

In order to achieve the objective of ensuring that the concept review provides an adequate opportunity to ensure the development of a national consensus on the direction Canada will take in this area, it is necessary that the EIS to be proposed by AECL address certain key specific areas.

Based on the present process for obtaining a societal response to the concept (public open houses in major cities, written notices in newspapers, and a mailed newsletter from the Environmental Assessment Review Panel) those who are likely to learn about the proposed concept, and who are likely to participate in the process, are a small and unrepresentative sample of the Canadian population geographically, culturally and socially. To solicit a broad

societal response to the concept, the public participation part of the process should include presenting the proposed concept in national electronic media: radio and television. Announcing and explaining the concept in terms of its rationale, the need for the project, the alternatives to the project and some discussion of the siting process that will follow a decision about the concept, would reasonably allow for a Canada-wide response to the proposed concept.

Section 9 References

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10.0 ECONOMICS AND FINANCING

Implementing the disposal concept would be a massive project, lasting many years. Economic and financing aspects of implementing the concept will have direct bearing on the feasibility of the proposed methodology and the timing of its implementation. The fundamental economic question concerning the concept is its cost and, in this regard, there are several key components which must be considered:

- methodology used in calculating total costs and evaluation of its accuracy;
- allowance for expected inflation and changing prices based on the anticipated time scale of the development; and
- availability of information used in calculations.

While the following discussion concentrates on the permanent disposal concept as developed by AECL, it should be noted that cost estimates for alternative disposal or storage options should also be provided by the proponents. Such information should be provided at a level of detail that will allow meaningful comparisons of the economic impacts of alternative options with the proposed concept.

10.2 Information Requirements

The appropriate amount and kind of information and the form in which it should be provided is influenced by the following:

- the nature of the decision process and its participants,
- the nature of the decisions to be made, and
- the characteristics of the concept to be evaluated.

The Nature of the Decision Process and Its Participants

Decision-makers with diverse backgrounds and different points of view, and using different decision paradigms, will be involved. For many of the decision models that might be used in the decision on acceptability of the concept, such as cost-benefit, cost-risk reduction, discounted cash flow project analysis, variables will have to be arbitrarily chosen and these choices will be open to debate. The choice of decision model itself is likely to be debated, since the length of time involved in the project may limit the meaningfulness of some of the traditional approaches to

decision making.

Accordingly, the proponents should concentrate on providing information which others can use in decision models of their choice, rather than choosing and applying models and providing the output. (The proponents may, of course, have used models such as cost-benefit analysis in selecting the least-cost alternative for achieving specified objectives within parts of the concept.)

Individuals and groups will be interested in different aspects of the project, such as the transportation of fuel waste or the mitigation of, and compensation for, social impact on the community. Similarly, individuals will be competent to comment on different specific aspects of the forecasted data such as the assumptions concerning the rate of growth of electrical usage or the availability of certain skilled labour in the year 2020. Others may concentrate on the estimating and forecasting techniques used or the justification for capital investments in parts of the concept, for example.

Accordingly, the proponents should be required to present information which is complete and sufficiently detailed to serve as input to a variety of decision models which will allow reviewers to conduct a wide range of analysis. All assumptions made and all estimates should be identified, justified and documented, so that they can be evaluated. Any estimates should be supported in detail; for example, for each part of the concept, the labour cost component should be separately set out and the labour hours and rates given.

The Nature of the Decisions to be Made

The acceptability of the concept will be at least partly a function of the amount that implementation of the concept would add to the marginal cost of nuclear-generated electricity. The concept, in all its aspects including cost, will be compared to alternative options for dealing with the fuel waste. (Should all options be found too costly, including the least-cost <u>acceptable</u> option, then this might be expected to be a constraint on the future use of nuclear generated electricity.) Clearly, the accuracy of the estimates of total cost of the options is important: the evaluation of that accuracy will require the ability to evaluate all component parts of those estimated costs.

In order to support the planning for financing the concept, the information provided should clearly include the time pattern of all expenditures. The planning of the financing of the concept (or alternative option) has several aspects. If the total estimated cost of the concept is found to be acceptable, it will still be necessary to construct a feasible plan for funding the proposal. A feasible financing scheme is one which the economy can bear; it must be co-ordinated with other needs for funding, which may be related to electricity generation (new generating stations or old ones decommissioned) or other social concerns such as facilities for the aged or other aspects of the environment.

The financing scheme must also reflect the chosen policy concerning the sharing of economic responsibility between user and future generations. Information on the time-pattern of expenditures will also allow the use of decision models involving discounting.

The Characteristics of the Concept to be Evaluated

The implementation of the permanent disposal concept will be perceived as a huge undertaking; a large project, lasting many years (probably approaching a century from date of approval) involving many different parts which are very diverse (a mine shaft, social impact mediation, nuclear waste transportation) and involving new technologies. It can be viewed as many separate projects, each of which would in itself be economically and socially significant, and this should be taken into account; the siting of the vault facility, the design and building of the community at the site, the design, siting and building of the needed roads and airport, could each in its own right be a major economic and social project.

Because individuals and groups will be competent to evaluate specific aspects of the concept, the concept should be broken down into its parts (e.g. facility siting, transportation and vault construction) and these parts broken into major elements. "Vault construction", for example, will include shaft drilling, underground transportation, ventilation systems, and grouting, each of which may be acquired in different markets, and involves different engineering expertise.

Where applicable, (for example, waste fuel storage, vault, site services) the cost of construction should be distinguished from the cost of operation. Operating costs should be broken down between fixed and variable to indicate the degree to which these

costs will vary with waste volume.

The cost should be broken down among material, labour, purchased services (for example, consulting and research), and overhead. Where it might be useful, costs should be further broken down: for example, expected labour costs might be broken down between unskilled labour and the major kinds of skilled labour, because these are in different parts of the labour market and subject to different supply forces. The same can be said of materials,where some will be readily available, others may be troublesome.

Expected Inflation and Changing Prices

How should the cost estimates reflect the fact that prices can be expected to increase over the duration of the concept? Should the estimated cost of labour in the vault in the year 2020 be presented in the wage rate expected to exist then, or in today's wage rate? In order to present all actually expected dollar amounts, it would be necessary to predict the path of all relevant prices, including wage rates, commodity prices, and services, throughout the life of the concept.

If that were done , and general inflation had occurred) prices generally had changed) then the estimated costs of each year would be stated in dollars of that year, dollars of different "real" or economic value, which makes them not properly comparable. Inflation causes a decline in the value of the dollar: as a result, a projected wage cost of $1,000,000 in 1995 would not represent the same economic significance as in the year 2015. This problem can be dealt with by using common dollars. This is done by choosing as a base the dollar at one point in time, and expressing the amounts at all other times in terms of that dollar. The usual base is the current dollar, the dollar as of the time of reporting.

Estimating future costs at then-current prices would be costly and difficult, and to the extent that price changes were due to inflation,would result in estimates which are not comparable in economic terms. As well, the estimates would lack credibility, especially given the long life of the permanent disposal concept. The proponent may wish to consider using today's (current) prices in estimating future costs. This is likely to be considered as a theoretically defensible solution as well as a practical one, because as shown below , the use of current prices results in the presentation of all cost estimates in common dollars. To use current prices is equivalent to predicting future inflation, and

future prices, and then converting those estimated costs into terms of current dollars. As noted below, this type of approach deals only with expected inflation (a change in the general level of prices) and not with specific price changes.

The cost should consider presenting estimates in today's prices, in current dollars, which will result in all cost estimates being expressed in common dollars, Any actually-expected "real" change in the price of an item of cost should be incorporated in the cost estimate, or, if the expected change in specific price is subject to too great a degree of uncertainty, it should be presented in a note to the estimates.

In summary, it should be recognized that the presentation of all estimates in current prices will result in the presentation of all costs in common dollars , but that this alone involves an implicit assumption that all specific prices will change with the general level of prices. If all costs are stated in current dollars, then all expected changes in specific price which are greater than the rate of inflation should be noted.

Uncertainty and Future Cost Estimates

The cost estimates will necessarily be based on a number of assumptions and estimates concerning the future. Maximum usefulness to users of the information requires full and adequate disclosure of the factors entering into the estimates:

- All assumptions that might have a material effect on the cost estimates should be identified and justified.
- All figures that are based on estimates should be identified and the sources and characteristics of the data on which the estimates are based should be identified
- Any limitations in the source data, or any caveats in the use of the data for that purpose, should be noted.
- Ontario Hydro has carried out some of the research on the concept. To the extent that future cost estimates are based on costs incurred in the past that have been allocated between the concept and Hydro's other operations, this should be disclosed and the manner in which the allocation was made described. Cost estimates based on expected future involvement by Ontario Hydro should be similarly dealt with.

- The estimating techniques used to generate the data should be identified and defended (sampling, regression, forecasting techniques).
- Where findings in the research literature are relied on, this should be noted and the sources identified.
- The degree of uncertainty attached to an estimate or assumption should be described in those situations where a high level of uncertainty is involved. Where the level of uncertainty attached to a potential estimate is so great that no defensible estimate can be made, the value used, or omitted as may be the case, should be explained and justified.
- For estimates or assumptions, the sensitivity of the total cost to that estimate or assumption should be stated where the sensitivity would be noteworthy. The sensitivity of the cost per unit of waste fuel to the forecast nuclear energy use should be specifically required, as giving an indication of the fixed/variable aspect of the concept.

Section 10 References

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11.0 MODELLING AND QUALITY ASSURANCE/QUALITY CONTROL

This section provides a general overview of modelling and quality assurance issues. A more detailed discussion of verification and validation of geosphere models is presented in section 7.4.

11.1 Model Evaluation

Quality assurance encompasses all the management and technical procedures that are directed toward ensuring and demonstrating that the product, in this case a model, is sufficient for its intended use. Quality assessment requires firstly that the intended use of the model be well-defined (i.e. what decisions will depend on specific model predictions and, based on this, what degree of error or uncertainty may be considered acceptable in the model outputs). Only within such a framework can it be determined whether model performance is sufficient to the task at hand. If it is not sufficient, then either the model or the input data must be improved.

Model evaluation practices have been described by ASTM (1984) and should include at least the following elements:

- model performance criteria (e.g. accuracy, precision of output);
- model examination (completeness of concept);
- model verification (correct mathematics and coding);
- data evaluation (adequate quality and quantity);
- model validation (agreement of prediction and measurement); and
- code comparisons.

Two key components of quality in an information product are accuracy and precision. Both means and variances can be compared in assessing agreement of predicted and measured distributions and model validations. Accuracy of a predictive model is always difficult to assess, particularly when the situation modelled is quite novel. We can only rely on past experience with similar situations (i.e. analogues) to determine whether components of the model are able to predict what actually happened. Several analogues are pertinent to deep geologic disposal of radioactive materials (e.g. Cigar Lake and Oklo). Model performance on these and other analogues should be documented in detail as part of the EIS process.

Estimating the precision of a predicted result is more tractable, using standard Monte Carlo techniques. SYVAC seems well suited to the task. The critical question that must be addressed is whether the uncertainty in the prediction is great enough to preclude initiation of deep geologic disposal at this time. The issue of how much uncertainty is too much obviously depends on the magnitude of the consequence prediction. We are more tolerant of uncertainty when the predicted consequence is far below any threshold of concern.

Monte Carlo methods primarily address input parameter uncertainty, and translate this into uncertainty in the final result. The range of possible input parameter values will depend, for many parameters, on the domain of study. After site selection, some of this uncertainty may be resolved by baseline monitoring.

Process uncertainty is more fundamental, and is not addressed by Monte Carlo methods unless input parameters are allowed sufficient range to encompass several alternative processes. This is not a good way to address process uncertainty; it is always preferable to understand the process and build this understanding into the model. However, where this cannot be done due to lack of process understanding, or due to the computer time demands of a rigorously defined process, it is important to identify any unresolved process issue and indicate which input parameter distributions incorporate this process uncertainty. Also, when a process is simplified for modelling purposes (e.g. solute transport in the geosphere model, GEONET vs. MOTIF), it is important to demonstrate that no bias has been introduced, or to identify conditions under which the simplified model may not be representative. When the detailed process is understood, the detailed and simplified models should be cross-calibrated, and calibration methods at both levels of detail should be described in the EIS.

Code comparisons can be useful in assessing process uncertainty in the model concept. When results obtained by different groups vary widely (i.e. poor consensus), this may indicate omission or inadequate representation of key processes. This is the principle behind interlaboratory comparisons in chemistry, when appropriate known standards are not available. In modelling, different groups working independently should produce similar predictions, if both groups are competent, and if the result is robust with respect to starting assumptions. Interlaboratory exercises of this nature have been performed under the auspices of HYDROCOIN, PSACOIN, etc. and results should be presented in the EIS.

All important processes that could strongly influence the model result should be explicitly represented in the model. Likewise, all event scenarios that could strongly influence the result should be considered in the modelling. Completeness checks should be performed and documented to provide such assurance. Lists of processes and events that have been considered should document the rationale for either inclusion or exclusion.

Coding and mathematical checks should be performed and documented to demonstrate that all equations are correct in theory, and correctly coded. Similarly, sub-model linkages should be checked to ensure correct matching of outputs and inputs, as well as consistent units on transfer.

Input parameter data may come from many sources. Often different data sets are combined to generate moments (e.g. mean, variance) for a single input distribution. Data verification checks should be performed and documented prior to data use. This screening procedure will address data reliability (i.e. reasonable values, valid methods of data generation), accuracy of data transcription into the host database, and suitability of the data for the present application. Often data are collected for one purpose and used for another; suitability for the original purpose does not imply suitability for the other. Finally, in combining data sets, careful attention must be given to consistent units, missing value identifiers, levels of censoring (e.g. detection limits) and censored data treatment. Inconsistencies here can create artifacts in the combined distribution.

Both pre- and post-closure models should be subjected to quality assurance assessment as outlined above. If there are differences in model performance criteria, these should be stated and justified, along with any differences in model structure, parameter lists or parameter input values.

11.2 Geosphere Transport Processes

The geosphere model in SYVAC will be based on equations that approximate the rock mass as an equivalent porous medium. However, it is not yet known at what scale it is possible to represent the transport process by an equivalent porous medium model. In evaluating the acceptability of the disposal concept, AECL should specifically address the basic uncertainty in the nature and modelling of field-scale solute transport processes in fractured rock environments. Progress in resolving some fundamental

questions is expected to lag behind the time frame for decisions on concept assessment.

Section 11 References

ASTM. 1984. Standard Practice for Evaluating Mathematical Models for the Environmental Fate of Chemicals. E978-84. Association for Standards in Testing and Materials. Philadelphia.